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Development of a Pressure Transducer Calibration System (Dynamic Pressure Response Calibrator) Phase II

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Current dynamic pressure calibrators are restricted in ultimate peak pressure, bandwidth, and accuracy; in fact, static calibrations are commonly performed for dynamic transducers. A dynamic transducer calibration system has been developed for the bandwidth of 2 to 2,500 Hz. Controlled pressure can be provided, in sine or random format, for a standard transducer and a test transducer. For the frequency bands of 2 to 150 Hz and 1,600 to 2,400 Hz, acoustic pressure levels up to 1.0 psi RMS can be attained. The development of this system demonstrated the application to acoustic-mechanical systems of a hybrid technique known as admittance modeling. (This technique combines experimentally derived test data with finite element model results.) The system can be used with a variety of dynamics tranducers.

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This report documents the development of a system for the calibration of dynamic pressure transducers. This work was performed for Arnold Engineering Development Center under SBIR Contract No. F40600-89-C0004. CSA acknowledges the efforts of Mr. Kevin Smith for his work on the original conceptual design and his assistance in the calibrator development. Special thanks to Mr. Jim Goodding of CSA for his work in supervising the testing phases of the project and for his innovative contributions.

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Contents

List of Figures

List of Tables

1. Introduction

Dynamic pressure transducers (sensors) are used in all phases of testing, qualification, and production of jet turbine and rocket engines. At Arnold Engineering Development Center (AEDC), engineers use a wide variety of pressure sensors and sensor/tubing configurations for jet and rocket engine development programs. Each individual testing situation may call for numerous tubing configurations, and each situation is unique in its own way. To ensure measurement reliability, frequent transducer calibrations are required.

This report documents work performed in the development of a calibration system for dynamic pressure transducers. The objective of this development program was to produce a calibration system for the sensor configurations in use at AEDC. In Phase I, the application to acoustic-mechanical systems of a hybrid technique known as admittance modeling was demonstrated. This technique combines test results and analysis data, and in this effort it was applied for a system with an acoustic pressure source and various acoustic cavities attached. In Phase I, a prototype dynamic pressure calibrator was built that was capable of achieving accurate and controlled pressure for several sensor configurations. The Phase II work carried these results forward and a self-contained calibration system that can be used for a variety of transducers was developed.

2. Background

Jet turbine and rocket engine dynamic pressure transducers are used for many purposes, including feedback sensing for pump shaft speed controllers, thrust measurement, and many "red-line" functions, such as overpressure indicators for solid rocket motors, secondary indicators for turbine over-speed, and unsteady combustion monitors. These sensors are installed at many turbine and engine locations, including pump inlet/outlet valves, radial and axial flow seals, combustion chambers, and nozzles.

Dynamic pressure sensors are often removed from the point of measurement by lengths of tubing, ducts in castings, or hollow rotating shafts. This offset might be necessary to provide thermal or chemical isolation or because of space constraints. Placing a precision pressure sensor in an exit nozzle or in a combustion chamber could lead to rapid failure. Also, the high temperatures of combustion and the corrosive nature of these gases (especially in solid-rocket motors) often require that the sensor is physically removed from them.

The pressure at the measurement surface is conveyed to the sensor with the tubing or duct. Typically there is little or no mean flow inside this tubing and it sometimes will have a heat sink or exchanger attached to it in order to prevent conducted heat from reaching the sensor. In some applications a pressure measurement must be made at a point where it would be difficult or impossible to place a sensor without extensive changes to the motor to accommodate the size of the sensor. Measuring pressure near a radial seal might require complete redesign of the bearing/seal/housing arrangement. But a small tube may be inserted into the housing and extended to the surface where pressure is to be measured. This tube can then be connected to the pressure transducer and the measurement made.

While tubing or duct configurations can solve problems associated with survivability of sensors, it is important to account for the effects of the intrinsic acoustic properties of the tube itself. A tube with one closed and one open end will behave like a resonator. If the closed end is replaced by a chamber, it is known as a Helmholtz resonator or filter. If the pressure quantity to be measured has a significant component at this filter's notch frequency, it is possible that tubing dynamics could be misinterpreted as resulting from system acoustics. The manner in which the tube is terminated at both ends is also very important. Small changes in diameter at mating joints will produce reflections and will have distinct filtering characteristics. Sharp bends, tees, branches, and other physical changes in the shape or diameter of the tube will result in complex and potentially undesirable characteristics. Even a perfectly straight tube has a fundamental resonance with overtones consisting of all odd harmonics.

Analytical techniques can be applied to describe a transducer system, but, because of the many factors involved, this tends to be more of an art than a science. For example, tubes that have compliant walls may be analyzed, but detailed knowledge of the material properties of the wall is required.

Because of these effects, the tubing, connectors/adaptors, and sensor should be calibrated together as a system. If circumstances require a tubing/sensor combination that has a notch or low-pass filter characteristic, then measurement bandwidth must be restricted to well below the limiting frequency. The calibration curve may be used not only as a means of determining sensor characteristics but directly as a gain/phase compensation curve if spectral content of the sensor signal is known. Some sophisticated controllers use this approach to extend the usable bandwidth of a sensor. This is the basis of the random-vibration servo-controller.

Calibration techniques have evolved which cover various types of pressure sensors, pressure ranges, bandwidth, accuracy, speed of calibration, cost of the calibration equipment, and skill level of the operator. The combination of performance factors called for in this project place the calibrator outside the bounds of typical and most specialized calibrators. For instance, the required bandwidth of 2–2500 Hz is easily achieved with many devices, e.g., a piston phone. But the ability to achieve this bandwidth at high pressures (up to 1 psi or 171 dB re .0002 μ-bar) with a random pressure field and good phase accuracy is beyond the capability of standard devices.

Many calibrators rely on the geometry, i.e., analytical knowledge of the acoustic properties of the calibrator, to produce predictable (but not controlled) acoustic fields. The sensor under calibration is usually assumed to have an input impedance that is very large compared to the source impedance. This assumption does not hold in this instance. The geometry of the tubing inlet/coupler is variable by definition and the input impedance is not necessarily large if the tube has acoustic resonances in or near the measurement bandwidth.

3. Objectives and Approach

The goal for the calibration system was to cover a wide dynamic range (2–2500 Hz) with a controllable pressure level (0.001–1.0 psi RMS, corresponding to a sound pressure level of 111–171 dB), a capability for both sinusoidal and random inputs, and adaptability to the various sensor configurations in use at Arnold Engineering Development Center.

A variety of pressure transducers are in use at AEDC. Multi-tine rake transducers typically have twelve, or fewer, tines, with tine outside diameters ranging from 1/16" to 3/16" and tine spacings of 3/16" or greater. Flush-mounted sensors with diameters up to 1/2" are also used, as well as tubing/sensor configurations with tubing diameters up to 1/4", tubing lengths to 36", and tubing volumes to 1.2 cubic inches.

The calibrator was developed as a rack-mounted self-contained unit with complete documentation of system operation as well as vendor-supplied manuals for the system components. Adaptability to the various sensors was achieved with individual mounting fixtures; prototype mounting fixtures were built for each type of sensor.

The Phase I development predicted that an acoustic compression driver could be used as the pressure source for a calibrator that would be capable of achieving 1.0 psi RMS over a frequency range of 2 to 500 Hz with sine excitation. However, Phase II tests with a more powerful driver/amplifier and with a more sensitive transducer system showed that this prediction was in error. To achieve the desired pressure range (1.0 psi RMS) over the widest possible bandwidth, a dual-excitation system was developed.

A schematic of the calibration system is shown in Figure 1. The system employs a digital servocontroller and power amplifier to provide controlled pressure spectra to the sensor under test and a standard (reference) sensor. The transducers are mounted so that they open into a small acoustic cavity in a mounting fixture designed so that the dynamic pressure at the reference sensor is equal to the pressure at the test transducer (or the pressure at the tubing inlet for a sensor/tubing configuration).

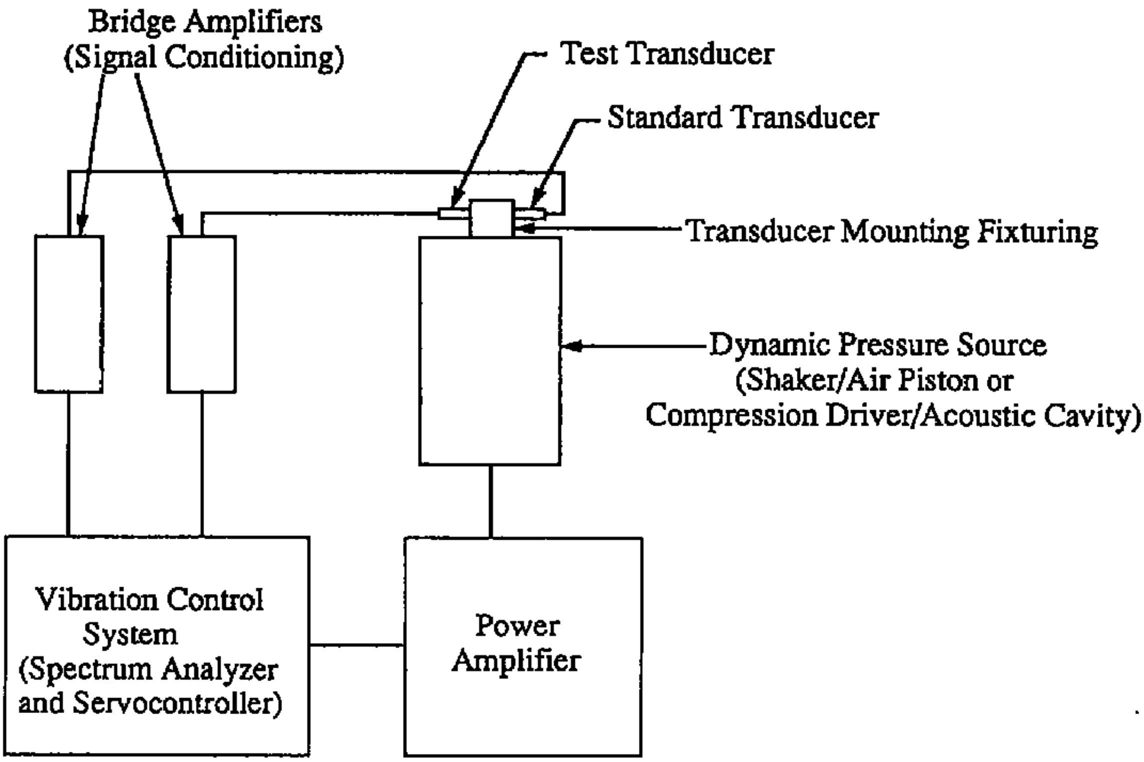


Figure 1. Schematic of equipment configuration for the calibration system

The dual system to provide the dynamic pressure consists of:

1. an electrodynamic shaker activates an air piston for the frequency range of 2–150 Hz, and
2. an acoustic compression driver is coupled with a custom acoustic cavity for the range of 150–2500 Hz.

For the low-frequency range, the shaker generates the dynamic pressure by moving a piston in a glass (pyrex) cylinder; for the high-frequency range, an acoustic cavity was designed and manufactured for use with the compression driver to maximize the acoustic pressure capacity at the transducers. The acoustic cavity design was optimized using a mathematical technique known as admittance modeling. Mounting fixtures which are interchangeable between the two pressure sources were developed for each of the three types of transducer. The capability of the system to meet the desired specifications, as well as the positioning of the transducers, was determined by test.

Preliminary testing indicated that the acoustic pressure goal of 1 psi was achievable at low frequencies with the shaker/piston configuration. However, for the high-frequency regime, testing showed that some form of amplification of the compression

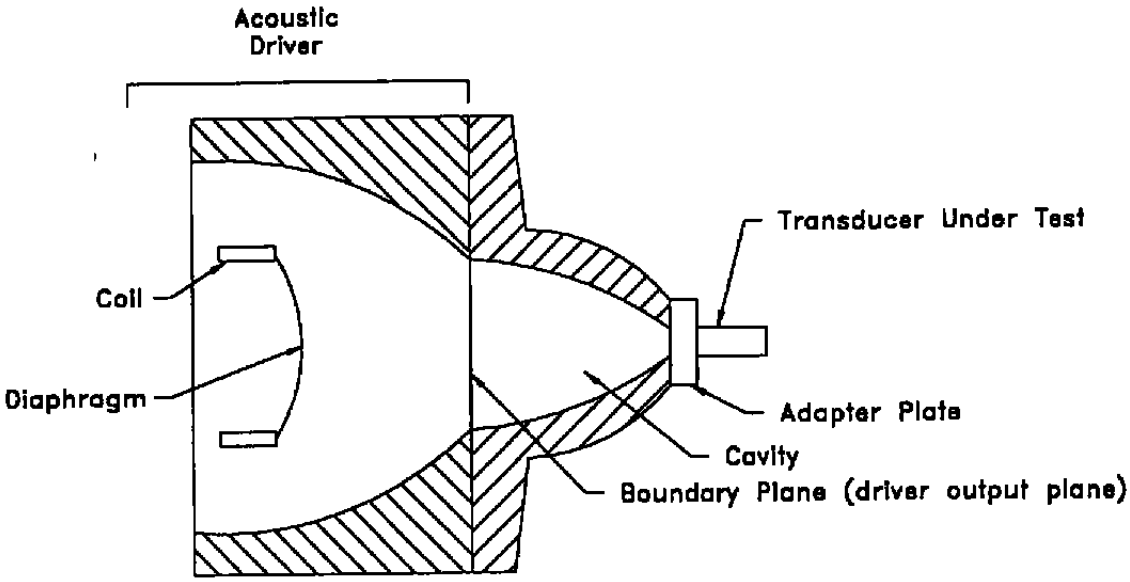


Figure 2. Cross section of pressure calibrator with acoustic driver as pressure source

driver's acoustic output would be essential. The mathematical modelling technique (admittance modelling) used to develop an acoustic cavity to provide this amplification is described in the following section.

4. Development of an Acoustic Cavity

4.1 Pressure Calibrator Admittance Model

This section describes the analytical method that was used to design an acoustic cavity for the compression driver portion of the calibrator (for the frequency range of 150–2500 Hz). Using admittances generated via both testing and analysis, this method was used for predicting acoustic pressure at the transducer location of an arbitrary cavity shape with a given electrical input applied to the driver. Figure 2 shows a simplified schematic of the compression driver apparatus for calibrating a pressure transducer. The sensor is mounted through the wall of a cavity which opens into the output port of an acoustic driver. It was desired that the calibrator be functional over the widest possible range of amplitudes and frequencies. To this end, the cavity shape was designed to concentrate acoustic energy near the sensor, without introducing large resonances and anti-resonances which the servocontroller would have to equalize.

The shape of the cavity was carefully chosen. It had to be efficient in producing a large acoustic signal at the transducer location for a given electrical input to the acoustic driver, while accommodating the fixed geometry of the acoustic driver at one end and a standardized transducer mounting fixture at the other. Design of the cavity amounted to balancing practical space constraints against acoustic performance. It required a method for predicting acoustic pressure at the transducer location of an arbitrary cavity shape when a given electrical input is applied to the acoustic driver.

4.1.1 Admittance Modeling – Background

The analytical method that was used is called admittance modeling. This modeling technique is used for modeling of multi-component dynamic systems in situations where one or more components are described in terms of measured frequency-domain data. For the development of the pressure calibration system, the combination of the acoustic driver and its power amplifier was such a component.

The defining characteristic of admittance modeling is that equations of motion are written in terms of physical (as opposed to modal) coordinates and in the frequency (as opposed to time) domain. The theoretical background of admittance modeling is covered in the users manual of the software package that implements the method. Entitled GAMMA, for Generalized Admittance Matrix Analyzer, the program was developed by CSA Engineering for vibration analysis of complex mechanical systems.[1] A copy of the GAMMA Users Manual was delivered to AEDC.

Application of the admittance modeling technique allowed the acoustic driver and power amplifier to be characterized entirely in terms of measured data. The description thus obtained was sufficient for predicting acoustic response at any point in a connected cavity of arbitrary size and shape. The cavity was described analytically in terms of an acoustic finite element model. GAMMA provided the software framework by which the experimental and analytical component descriptions were combined and the resulting system model was exercised to obtain response predictions.

The theory of admittance modeling is equally applicable for the cases of sine, general periodic, transient, or stationary random input to the acoustic driver. Fourier transform theory provides the common analytical foundation. In the explanation that follows, it is convenient to consider the case of a special periodic input, namely a pure sinusoid. Variables such as p (pressure) and v (particle velocity) can then be represented in terms of a complex Fourier series having only a single term. P and V become the single complex Fourier coefficients of those series. Relative phasing information is carried by the arguments of the complex coefficients.

For transient inputs, P and V are ordinary continuous Fourier transforms. When the variables of interest are stationary random, their Fourier transforms can be related

[1]GAMMA Users Manual, Version 1.2, CSA Engineering, Inc., April, 1989.

to power spectral density functions by the usual methods of random processes.[2] The point is simply that, while admittance modeling can be applied for many types of input waveforms, it is most easily explained in terms of sine excitation.

Finally, an explanatory note is in order for the reader who might wish to use the GAMMA Users Manual as tutorial material in order to understand the modeling method. The examples in the manual, and in fact the entire program, were developed with structural applications in mind. In such cases, one is usually concerned with motion responses to force or motion inputs. The examples in the manual are therefore cast in that format. When applied to acoustics, this can lead to some confusion in terminology as explained below.

It can be shown that three-dimensional acoustic problems, in the absence of convective flow, can be treated in terms of an "equivalent" solid mechanics problem.[3] The most computationally tractable method for doing so (the method in use on this project) uses the following analogy. Displacement in a single direction in the solid problem corresponds to pressure deviation in the acoustic problem. Force in the solid problem becomes analogous to the time derivative of volume rate, i.e., the product of area times acceleration. The practical consequence is that an admittance function in structures (ratio of motion to a single input force) becomes analogous to impedance (ratio of pressure to a single input motion) in acoustics. This accounts for the difference in terminology; "impedance" in acoustics plays the role of "admittance" in structures.

4.1.2 Calibrator Admittance Model – Overview

For the calibration system, an equation was derived to predict the ratio of pressure to drive voltage at a sensor location in an arbitrary acoustic cavity which was modeled analytically. This equation was written in terms of

- frequency response functions (transfer functions) which were actually measured, and
- acoustic impedances which were generated via finite element analysis.

A roadmap of the mathematical description that was derived is shown in Figure 3.

4.1.3 Admittance Modeling Tests

This section describes the tests by which a mathematical description of the acoustic source was obtained. The tests characterized the acoustic source: from the power

[2]Bendat, J. S., and Piersol, A. G., "Random Data: Analysis and Measurement Procedures," Chapter 2, Wiley-Interscience, 1971.

[3]"MSC/NASTRAN Handbook for Dynamic Analysis," Section 7.3, MacNeal-Schwendler Corp.

F.E. analysis

measured FRF (blocked plate test)

$$\frac{\text{Pressure at sensor}}{\text{Drive voltage}} = W_{C2} = \frac{Z_{C12}}{Z_{C11} + \underbrace{Z_{D11}}_{\text{output impedance of driver}}} W_B$$

= ρc (acoustic theory)

$$\overbrace{Z_{D11}} = \left(\frac{W_B}{W_T} - 1\right) Z_{T11}$$

measured FRF (infinite tube test)

Figure 3. Mathematical description of calibrator admittance model

amplifier signal input to the pressure output at the mouth of the acoustic driver. The admittance model was complete in the sense that it allowed calculation of the acoustic pressure anywhere in an arbitrary cavity. This pressure, of course, depended also on the characteristics of the cavity.

The procedure described below is a variation of the "equivalent excitation" problem described in the GAMMA Users Manual. This problem, which occurs frequently in applied structural dynamics, was the original motivation for the GAMMA code. As will be obvious, the procedure of the example problem was modified somewhat for the present acoustics application. This was necessary because of measurement limitations. In structures, we can measure motions and forces equally well. However, in acoustics we can only measure pressures. The acoustical conjugate variable (air particle motion) is mathematically significant but impractical to measure. The test procedure described below was devised to work around this limitation.

The notation used in the derivation of the model follows the usual notation of admittance modeling,[4] illustrated schematically in Figures 4 and 11. The complex quantity P represents the amplitude and phase of pressure and Z represents a complex acoustic impedance. Acoustic impedance is P/V where V is the complex amplitude/phase of particle velocity in the direction of acoustic wave propagation. The subscript D indicates the driver and C indicates a cavity into which the output of

[4]Ibid., GAMMA Users Manual.

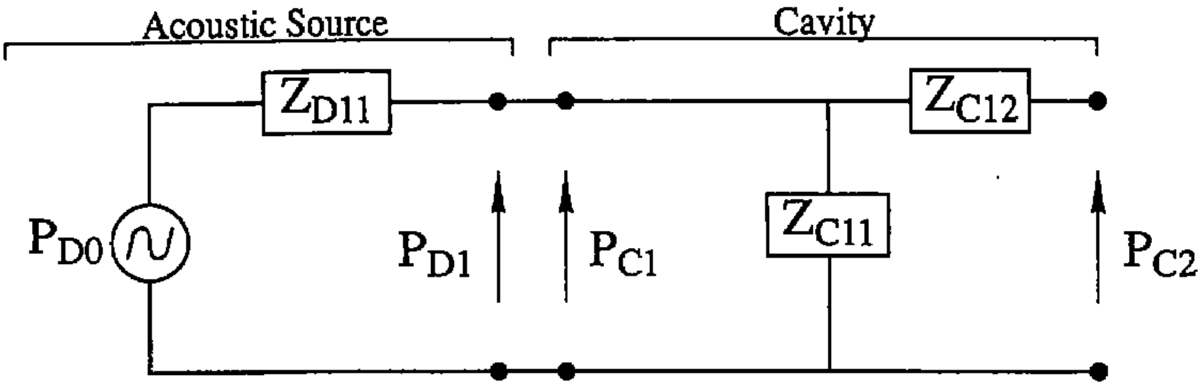


Figure 4. Admittance model of acoustic pressure source and test cavity

the driver is directed. The subscript T denotes a special type of test cavity, namely a long tube of constant diameter. P_{D1} refers to the pressure at point 1 of the driver (a point on the output plane). Z_{C11} is the driving point impedance of the cavity, i.e., the impedance P_{C1}/V_{C1}. Z_{C12} is a crosspoint impedance of the cavity (P_{C2}/V_{C1}); P_{C2} and V_{C1} represent variables at different spatial points in the cavity. Point 1 is in the boundary plane between the driver and cavity and point 2 is near the "output" of the cavity, i.e., the transducer being calibrated.

Figure 4 shows an admittance model of the acoustic pressure source. It is composed of an ideal pressure source P_{D0} in series with an acoustic impedance Z_{D11}. These two elements are called, respectively, the active and passive parts of the admittance model. They represent an equivalent excitation model of the acoustic source. It is equivalent to the real source in that both produce the same pressure, $P_{D1}(= P_{C1})$, at the boundary plane when connected to an arbitrary load. P_{D0} is simply part of the equivalent admittance model; it is not necessarily the physical pressure at any specific point in the driver. Z_{T11} represents a passive test load. It is the driving point impedance of some connected cavity.

It was assumed that the acoustic pressure field is uniform over the mouth of the cavity. This was equivalent to assuming that the two components are coupled at only a single degree of freedom. This approximation allowed the use of complex scalar quantities (1×1 matrices) rather than ($n \times n$) complex matrices, as would be the case if the coupling were more general. Nonuniformity of the pressure field (i.e., coupling at multiple degrees of freedom) can be accommodated by GAMMA if necessary. This is a primary feature of the code, but it greatly increases the computation time and is used only when required.

The data-acquisition part of the modeling consisted of two tests.

4.1.3.1 Blocked Pressure Test

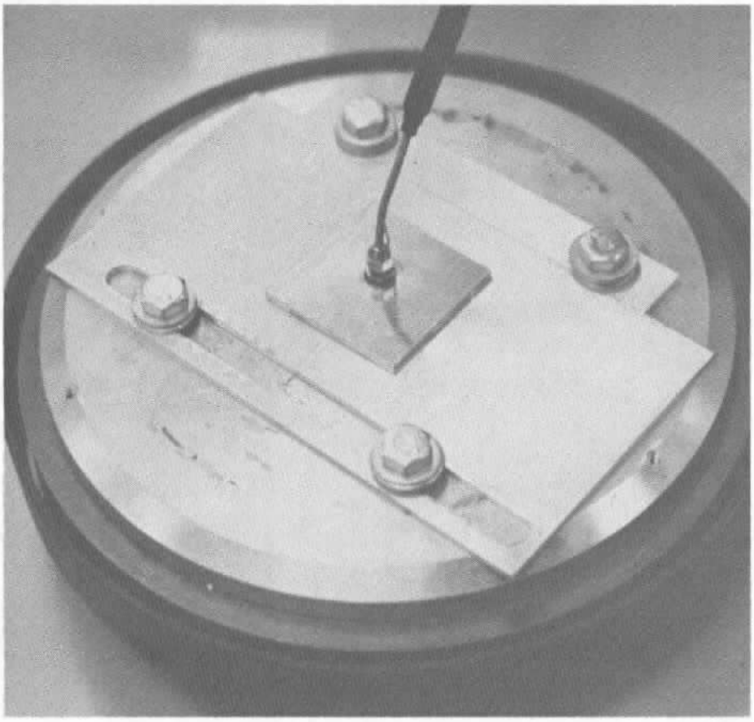
The first test was performed by connecting the source to a very high acoustic impedance, which was modeled as infinite. This was simply a blocking plate that completely closed off the output port of the driver. A sinusoidal drive signal was applied to the driver power amplifier and the pressure P_{D1} was measured at the driver exit plane by a transducer flush-mounted through the blocking plate. Since V_{D1} was constrained to be zero, no "current" flowed through Z_{D11}, and P_{D0} was equal to P_{D1}. Thus, P_{D0}, the active part of the admittance model, was measured. This term will also be referred to as P_B, or the "blocked" pressure.

The blocked pressure test configuration, shown in Figure 5, was assembled, consisting of the servocontroller (supplying the controlled drive signal), the power amplifier, a resistor bank at the driver input to provide current measurements, the acoustic driver with a blocking plate containing a pressure transducer, and a signal conditioning amplifier.

The blocked pressure test was performed over a frequency range of 2.0 to 2500.0 Hz (swept sine) with the servocontroller providing a constant 0.1 psi zero-peak reference pressure. The power amplifier gain was maintained at a constant level during testing. The measured transfer function, *blocked pressure/voltage input to the power amp*, was recorded at several locations, at the center of the driver opening and at 0.25-inch intervals along the radius of the opening, to determine the required functional representation of the interface of the driver and cavity in the admittance model. (The transfer functions at seven equally-spaced intervals were virtually identical below 1000 Hz and within 3 dB over 1000 Hz.) These measurements validated the assumption made in the derivation of the admittance model that the acoustic pressure field is uniform over the mouth of the cavity. The measured admittance function representing P_{D0} is shown in Figure 6. This function is referred to as W_B, or the transfer function of *pressure/voltage input to power amplifier* measured at blocking plate across the driver.

4.1.3.2 Known-Impedance Test

A similar measurement was performed with the driver connected to a cavity with a finite and known impedance. A tube of infinite length satisfies this requirement; a practical choice for this test was a long rigid tube with an inside diameter equal to



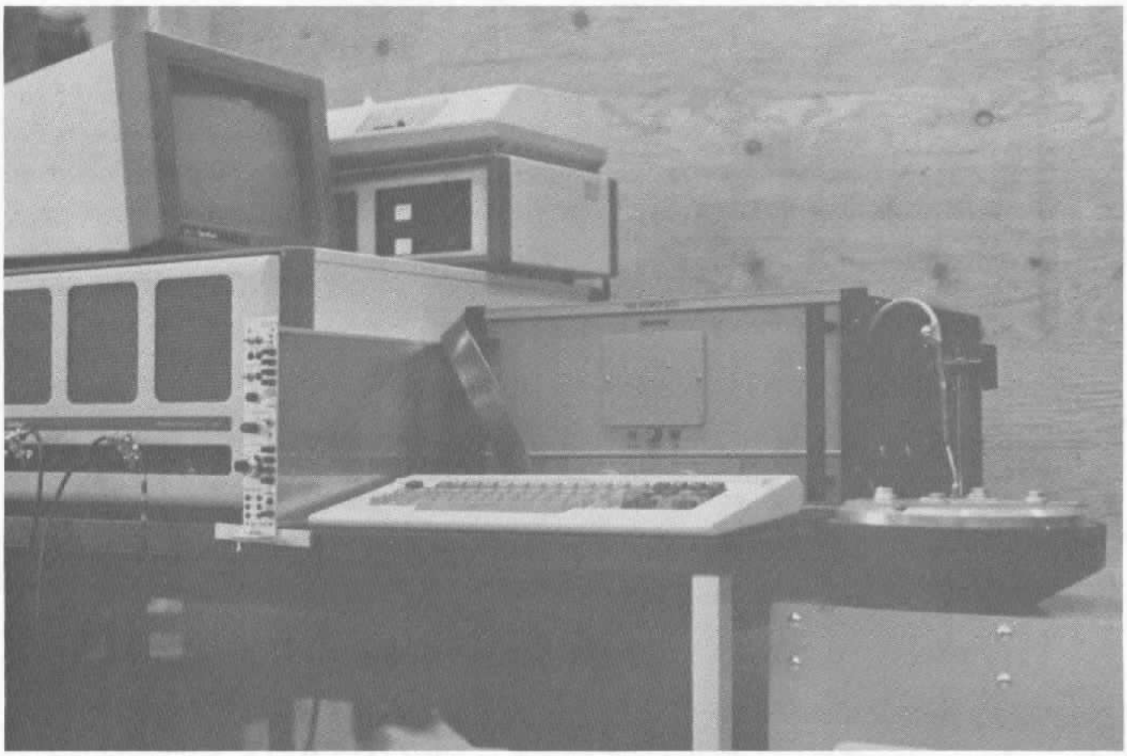


Figure 5. Equipment configuration for blocked pressure test

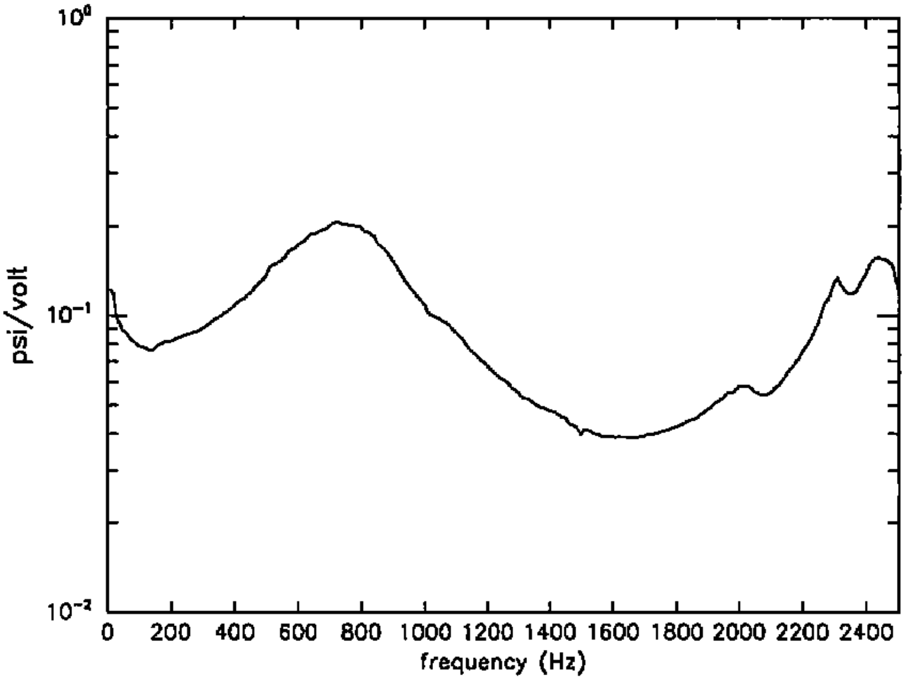


Figure 6. Transfer function of *pressure/drive voltage* measured at blocking plate across driver

that of the driver output port. The tube had to be long enough to approximate the acoustic characteristics of an infinitely long tube. (It will be shown how measurements taken using this tube of finite length were used to generate the equivalent data for an "infinite" tube.) The load impedance, called Z_{T11}, was then real, constant, and equal to ρc, the product of air density and sound speed.[5] The pressure at the interface plane, designated P_{T1}, was measured by a transducer mounted through the tube wall near the driver mouth.

The hardware used for the known-impedance test consisted of two twenty-four foot lengths of aluminum tubing with inner diameter equal to the diameter of the driver mouth (3.2"). Pipe flanges were machined to join these tubes together (creating a 48-foot-long "infinite" tube) and to attach the end of one tube to the driver. The known-impedance test configuration is shown in Figure 7.

Measurement of the frequency response function W_T presented a special problem. It is defined in terms of the driver output pressure when connected to an infinite tube. The longest practical tube (48') cannot give a good approximation of an infinite tube at low frequencies. The solution was to use a fast transient (burst random) input to measure the frequency-averaged FRF. The latter can be shown[6] to

[5]Kinsler, L.E., and Frey, A. R., "Fundamentals of Acoustics," Section 5.8, Wiley, 1962.
[6]Lyon, R. H., "Statistical Energy Analysis For Designers," AD/A-006 413 (Section 2.3), 1974.

be the FRF of the infinite extension of the actual tube. Physically, the measurement procedure is most easily visualized in terms of traveling acoustic waves rather than normal modes ("standing" waves). One simply uses a short transient signal as the input and measures only the first passage of the outgoing wave. The measurement is completed before the arrival of the first reflection from the tube end and hence is insensitive to tube length. The resulting short record length produces a rather coarse frequency resolution (reciprocal of record length) which is, in effect, equivalent to frequency averaging. The test was accomplished with a burst random signal generated and recorded using CSA's burst-gate generator and Zonic modal test system. Fifty individual measurements were averaged to provide a clean transfer function. The measured admittance function representing P_{T1} is shown in Figure 8.

4.1.4 Calculation of Equivalent Source Impedance for Driver

The impedance of the acoustic driver, Z_{D11}, was calculated as follows. The (unmeasured) particle velocity in the known-impedance test was

$$V_{D1} = V_{T1} = P_{T1}/Z_{T11} \tag{1}$$

Considering the left loop of the circuit in Figure 4,

$$Z_{D11} = (P_{D0} - P_{T1})/V_{D1} \tag{2}$$

Combining (1) and (2) gives the desired result

$$Z_{D11} = ((P_{D0}/P_{D1}) - 1)Z_{T11} \tag{3}$$

Z_{D11}, the passive part of the admittance model, completes the description of the acoustic source. Note that, of the three quantities on the right in Equation (3) above, two were measured pressures and the third was a known, constant impedance depending only on air properties.

4.1.5 Acoustic Cavity Designs

Cavity designs were formulated using the SDRC/I-DEAS solid modeler on a Silicon Graphics Personal IRIS workstation. Initially, the designs generated were rough geometric shapes. These were installed into the admittance model to provide information about what shape of cavity to pursue. Finally, shapes were developed such that

- a mounting fixture for a reference sensor along with a rake tine, flush-mounted transducer, or tubing end could be accommodated at the output end of the cavity, and

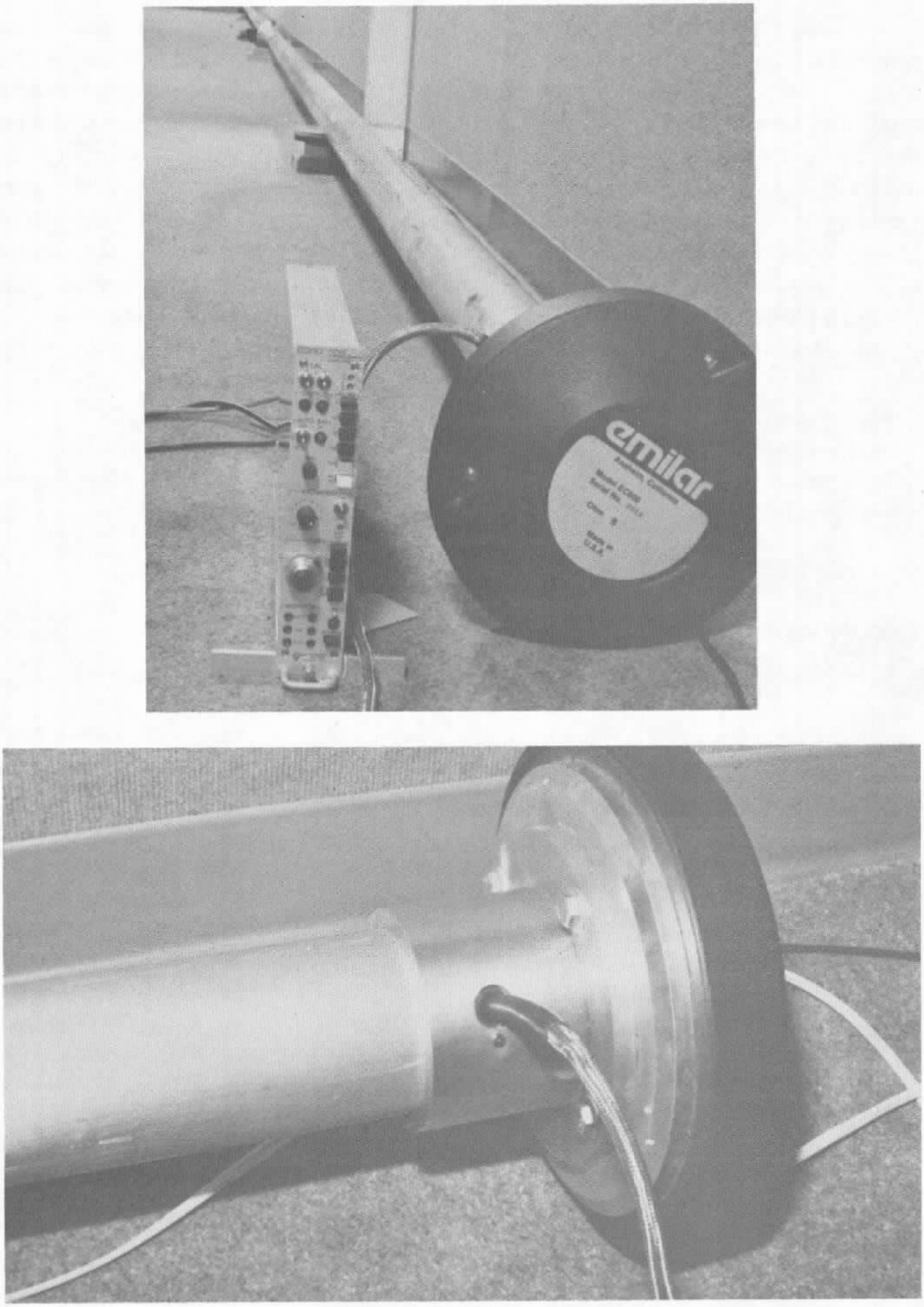


Figure 7. Equipment configuration for known impedance test

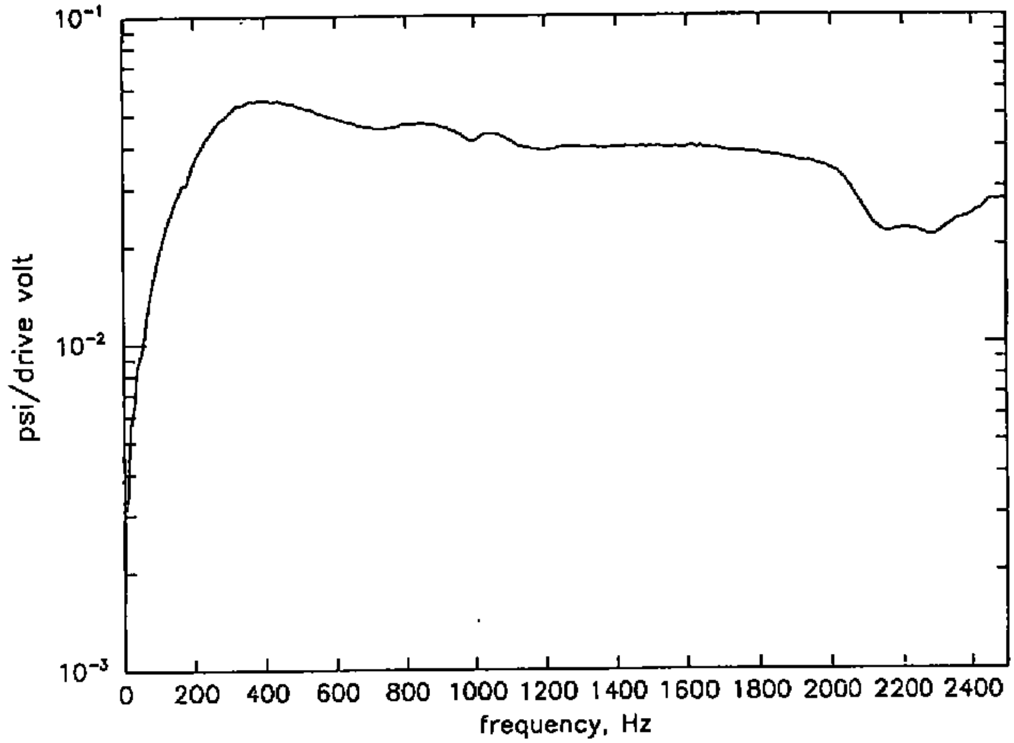


Figure 8. Transfer function of *pressure/drive voltage* measured at driver directed into "infinite" tube

- the diameter of the cavity where it is bolted to the driver is equal to the diameter of the driver opening.

Four solid models of cavities are shown in Figure 9. Using the mesh-generating capability of I-DEAS, finite element models were created for each of these cavity shapes. Acoustic dynamic analyses of the finite element models were performed with MSC/NASTRAN, and frequency response functions were then generated using GAMMA to obtain the impedances Z_{C12} and Z_{C11} for the admittance model. Figure 10 shows the finite element mesh for a candidate cavity design.

4.1.6 Combined Admittance Model of Acoustic Source and Cavity

A system model of the combined acoustic source and cavity was assembled. Figure 11 shows the model. It is similar to Figure 4, except that the acoustic load on the source is the input impedance of the actual cavity, Z_{C11}, rather than that of the test cavity, Z_{T11}.

Z_{C11} is the driving-point impedance of the cavity, i.e., the ratio P/V at the cavity mouth. It is independent of the driver properties and was calculated from an acoustic finite element model of the cavity using the solid analogy described previously. The finite element model was also used to compute a crosspoint impedance for the cavity.

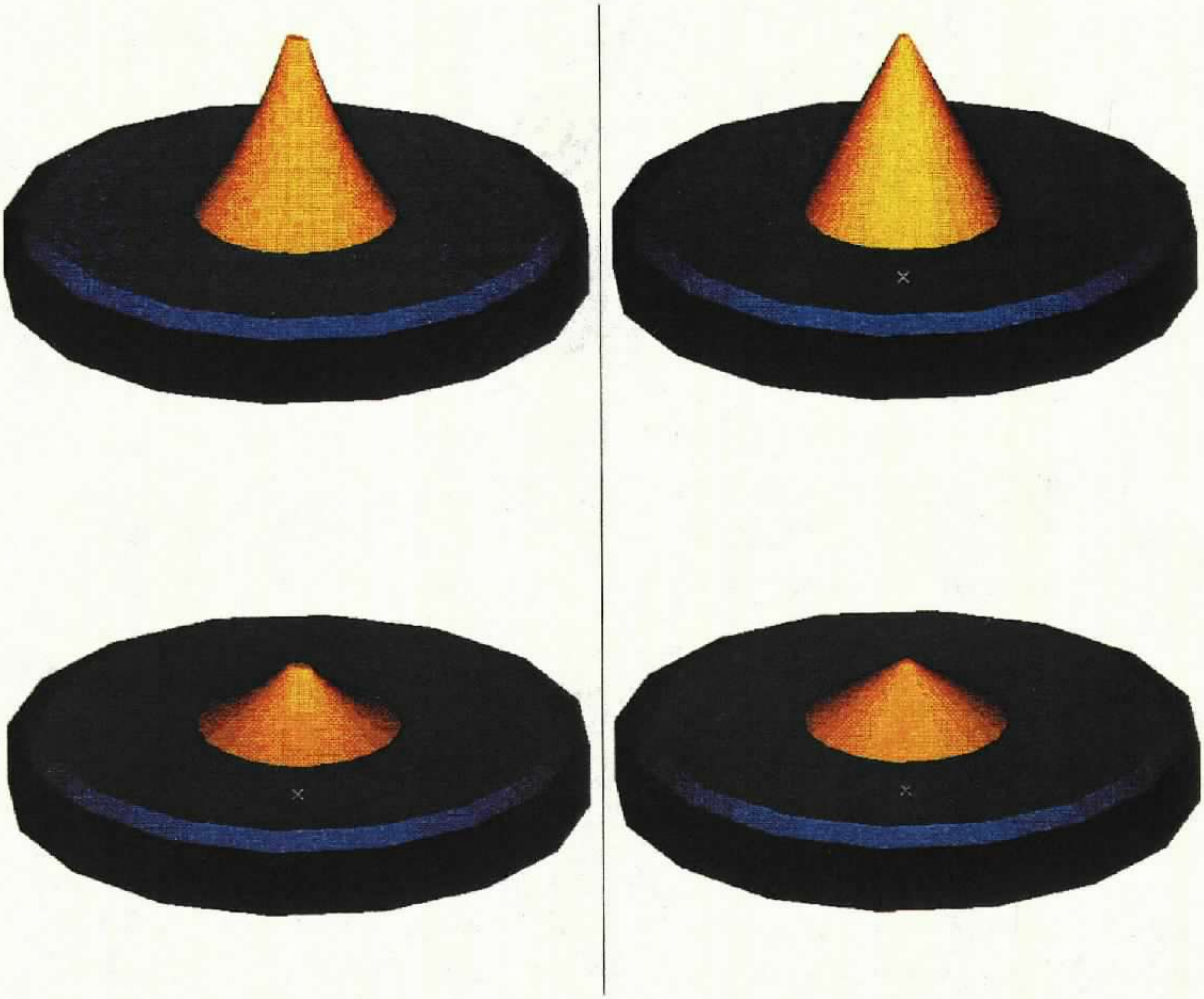


Figure 9. Candidate acoustic cavity designs

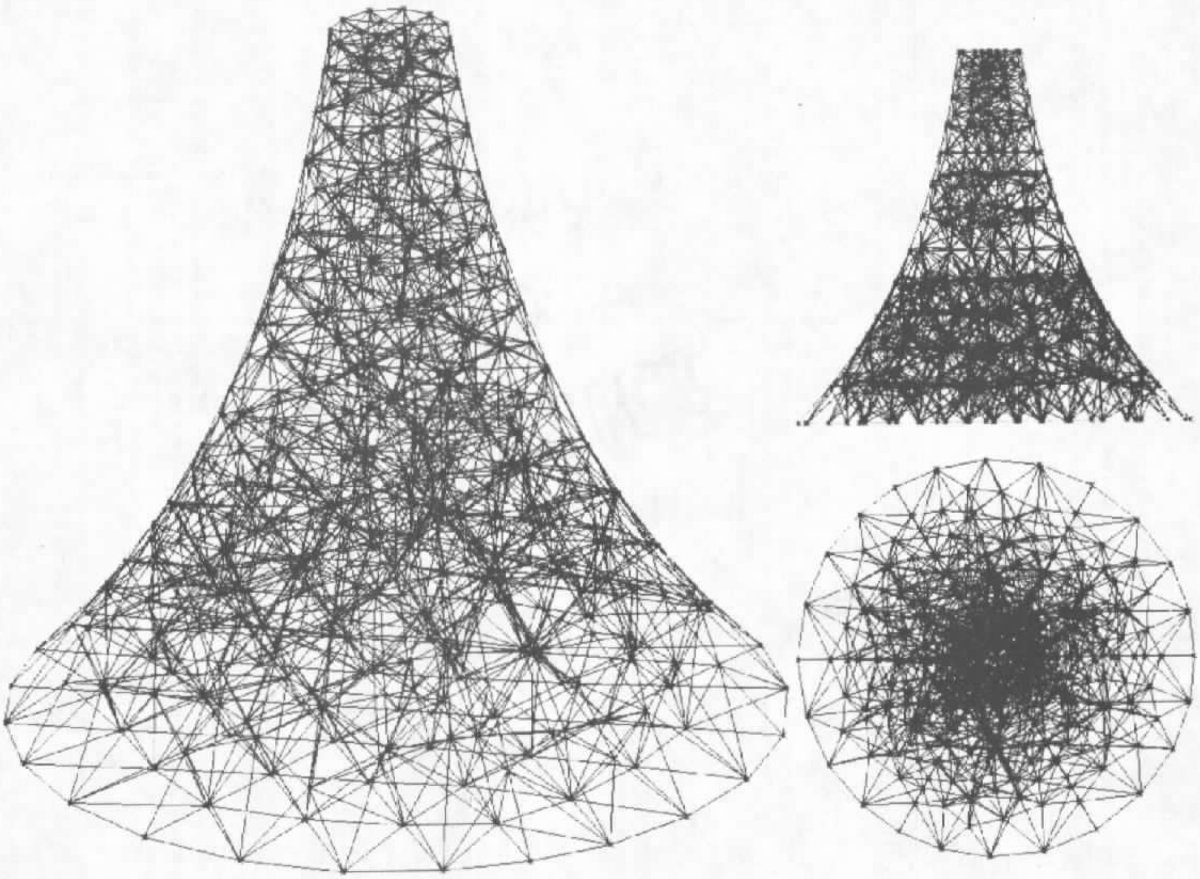


Figure 10. Finite element mesh for a candidate acoustic cavity design

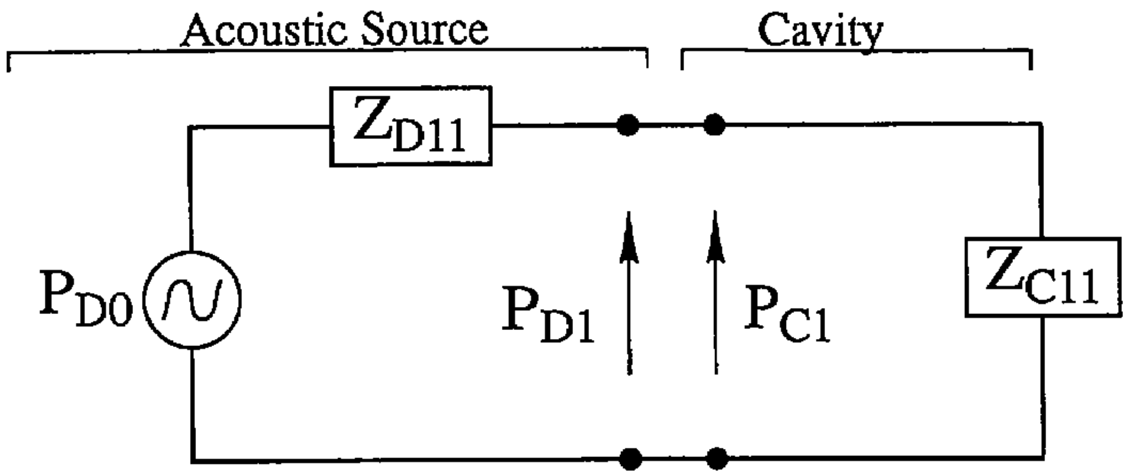


Figure 11. Admittance model of the acoustic source and cavity

$$Z_{C12} = P_{C2}/V_{C1} \tag{4}$$

P_{C2} is the pressure at the location of the transducer. V_{C1} is the particle velocity at the cavity inlet end (the connection to the driver). While particle velocity cannot be directly measured, it was, for this case, easily calculated.

Considering Figure 11, P_{D0} and Z_{D11} were known from measurements on the acoustic source. Z_{C11} was known from the finite element model of the cavity. The interface pressure could then be calculated. The two impedances in series are simply a "voltage" divider. The pressure P_{C1} at the interface is

$$P_{C1} = (Z_{C11}/(Z_{C11} + Z_{D11}))P_{D0} \tag{5}$$

The particle velocity at the interface is, from (5) and the definition of Z_{C11}

$$V_{C1} = ((Z_{C11}/(Z_{C11} + Z_{D11}))P_{D0})/Z_{C11} \tag{6}$$

Finally, the calculated cross impedance Z_{C12} is used with (4) and (6) to calculate the output pressure P_{C2}.

$$P_{C2} = (Z_{C12}/(Z_{C11} + Z_{D11}))P_{D0} \tag{7}$$

Defining a quantity

$$W = pressure/drive\ voltage \tag{8}$$

casts equation (7) in a more convenient format.

$$W_{C2} = (Z_{C12}/(Z_{C11} + Z_{D11}))W_B \tag{9}$$

Here W_B is the blocked pressure transfer function, measured directly, and W_{C2} is the transfer function of pressure over drive voltage at any transducer location in a specified cavity. The function W_{C2} can be compared directly with W_B to determine the amount of (pressure) gain that can be expected from a particular cavity design.

4.1.7 Implementation of Admittance Model into GAMMA

The matrix functions (transfer functions and impedances) and admittance equations of the model were written in GAMMA format. This involved setting up the appropriate commands in the GAMMA language to input the mathematical formulations for these functions and impedances generated from test and analysis. The basic commands of the GAMMA formulation are given in Appendix A. In the GAMMA language, text on a command line following the symbol ! represents a descriptive comment and is ignored by the code. This command sequence is presented as an example to assist users of the GAMMA code.

4.1.8 Admittance Model – Summary

Equation (9) shows how admittance modeling allows measured and calculated component descriptions to be combined to allow predictions of output response, in this case a transfer function of *acoustic pressure/drive voltage*. W_B is a property of the acoustic source and was measured directly via the blocked-pressure test. Z_{D11} is also a source property. It was indirectly measured using results from the blocked-pressure and known impedance tests. These tests provided a complete description of the acoustic source.

Z_{C12} and Z_{C11} are calculated properties of the cavity. They were obtained by finite element methods and used in Equation (9) to evaluate candidate shapes for the cavity. The finite element work was aided by the use of the I-DEAS automated mesh generator for dividing the cavity into three-dimensional solid elements. Computational requirements are modest for acoustic analysis (as opposed to structural analysis) because each grid point has only a single degree of freedom.

In the foregoing, it should be clear that the impedances Z_{D11}, Z_{C11}, etc., whether measured or calculated, are complex functions of frequency. Likewise, complex transfer functions such as W_B and W_{C2} are measured or calculated separately for each frequency of interest. GAMMA includes extensive complex block arithmetic functions to allow calculations such as Equations (3) and (9) to be performed at several hundred frequencies at once with a minimum of user effort. GAMMA can perform such calculations with equal ease when the pressure quantities and impedances are matrix functions of frequency. This situation occurs when system components are coupled at multiple degrees of freedom.

In practice, it is often convenient to use random (rather than sinusoidal) excitation to perform the measurements required in assembling an admittance model. Conceptually, this is similar to exciting the system with many frequencies at once and using digital Fourier signal processing to sort them out. The theoretical basis remains essentially the same and the response calculations (Equation (9)) can still be performed using the GAMMA program. For this project, sinusoidal excitation was used for the blocked pressure test because of software limitations. GAMMA requires the real and imaginary parts of a transfer function to provide the necessary phase information, and the servocontroller (using the current version of the GenRad software) will provide output in this format only with sinusoidal excitation. Random excitation was used for the known impedance test using CSA's Zonic modal testing system.

4.2 Selected Cavity Design

Finite-element representations of numerous acoustic cavity designs were created, and the admittance model was executed using the impedances generated from these analyses. The resulting transfer functions, *pressure at the transducer location/drive voltage*, were plotted for each design. Figure 12 shows the transfer functions for four representative designs. This figure compares these transfer functions to the blocked pressure transfer function to illustrate the amplification capability of the various cavities.

It is clear from the comparison of the transfer functions that cavity size and shape strongly affect calibrator performance. It became evident after iterations on the model that the best general shape for the cavity was a "reverse" acoustic horn, with the input (acoustic driver connection) at the large-diameter end and the output (transducer mounting) at the end with the small diameter.[7] The diameter of the cavity at the base (3.2") was fixed by the geometry of the acoustic driver. The cavity diameter at the top (0.5") was chosen because it was large enough to accommodate a mounting fixture for the reference sensor with any of the desired test sensors, yet small enough to provide a reasonable flare constant. (Larger flare constants, corresponding

---

[7]The cross-sectional area of an acoustic horn is a function of the axial distance from the small-diameter end, given by

$$S_x = S_0 e^{mx} \tag{10}$$

where

$$S = \textit{cross sectional area} \tag{11}$$

$$x = \textit{axial distance from the end of small diameter} \tag{12}$$

and

$$m = \textit{flare constant} \tag{13}$$

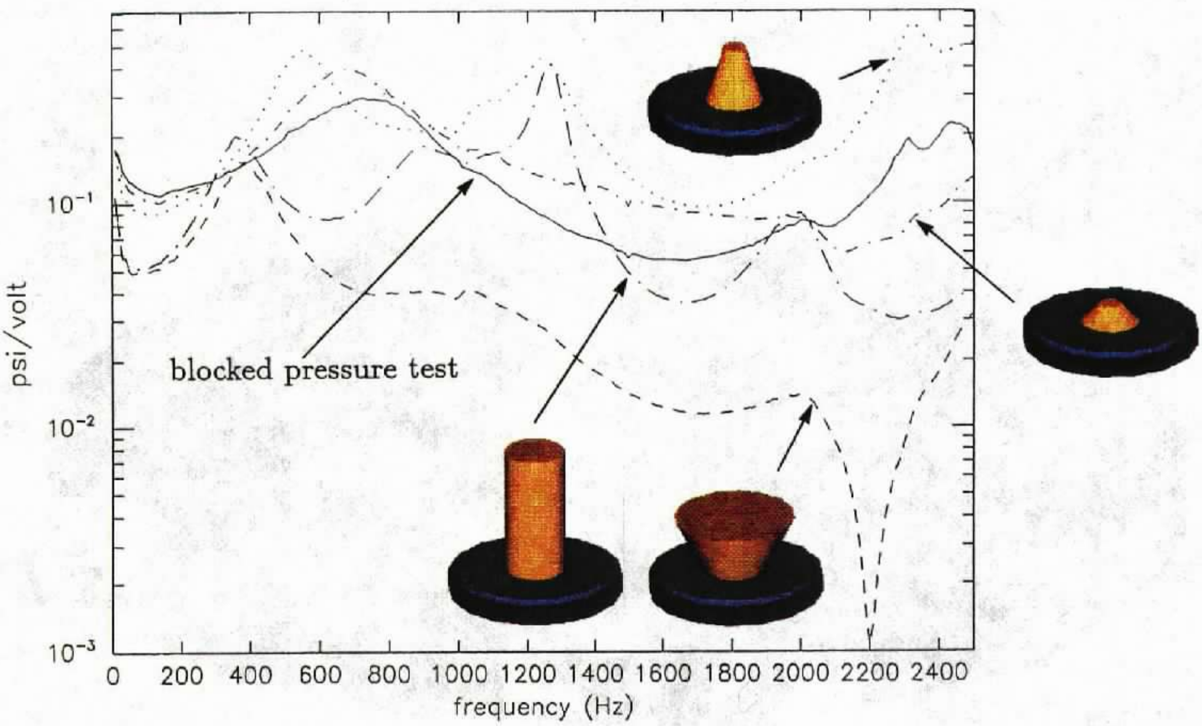


Figure 12. Comparison of transfer functions, *pressure at transducer location/drive voltage* for four candidate cavity designs and blocked pressure configuration

to smaller top diameters, produced better pressure amplification, but 0.5" was the minimum practical top diameter for the transducers to be tested.) The cavity design that produced the best result was three inches in height, tapering exponentially from the driver opening to the top of the cavity. This design is shown in Figure 13.

The acoustic cavity was machined from aluminum bar stock on an NC lathe. A special tapered boring bar was required to produce the exponential taper on the interior of the fixture. A photograph of the cavity fixture mounted to the compression driver is shown in Figure 14.

To verify the amplification capability of the cavity as predicted by the admittance model, an adapter plate was machined to mount a transducer at the output end (transducer location) of the cavity, and a test was performed to measure *pressure/drive voltage.* Comparison of this test result with the model prediction is presented in Section 8 of this report. The acoustic pressure spectrum generated with the combination of compression driver and cavity was not exactly as predicted by the model, but the amplification obtained in the upper frequency range was considered sufficient to proceed with the development using this design.

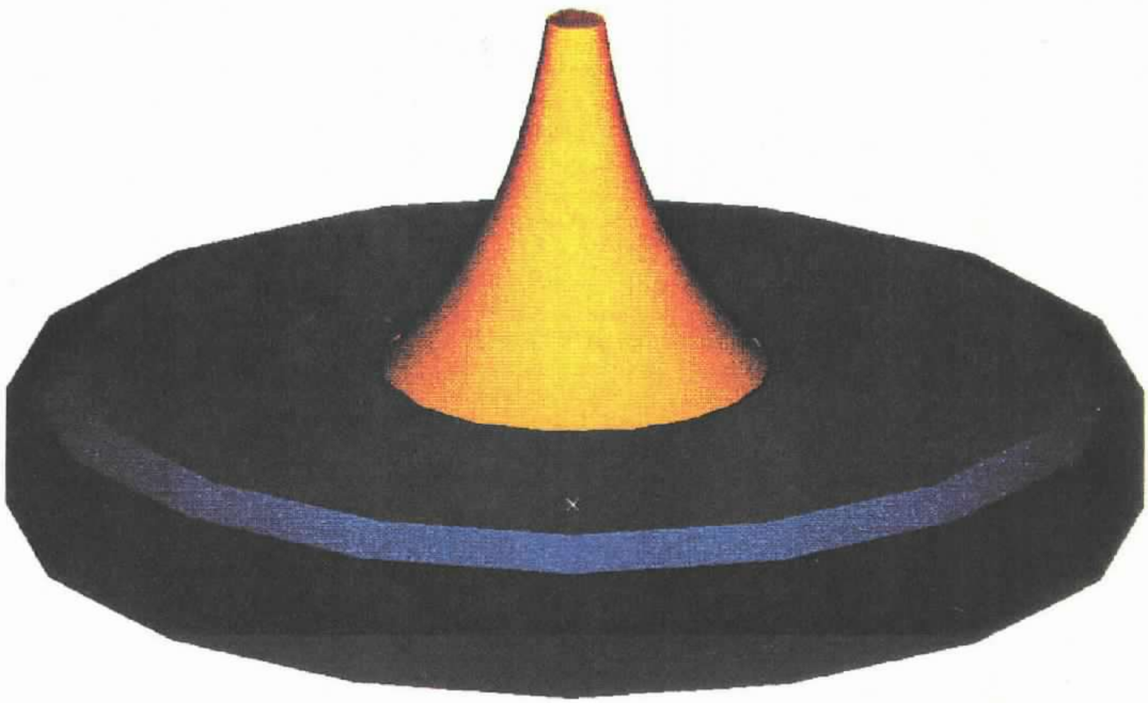


Figure 13. Selected cavity design

5. Electrodynamic Shaker/Air Piston Development

Testing performed in Phase I indicated that the shaker/piston configuration would be adequate for the calibration system's low-frequency regime. The only additional development for this component of the system was to design fixturing

- to support the air piston on the shaker body, and
- to provide a mounting location for the transducer fixturing.

The shaker that was used in the preliminary testing was a VTS-100 shaker from Vibration Test Systems. This shaker has a dynamic rating of 100 pounds and a stroke of 3/4 inches peak-to-peak. It was decided to continue with this unit for the shaker/piston configuration.

The VTS-100 shaker body has three equally spaced tapped mounting holes on its top surface. However, the flexures supporting the shaker armature would interfere with fixturing that was attached using two of these holes. For this reason, the shaker surface was re-machined with a four-hole pattern to accommodate fixturing.

The fixturing for the shaker was machined from a single piece of aluminum bar stock. The air piston is supported inside the fixture with O-rings. An O-ring is also

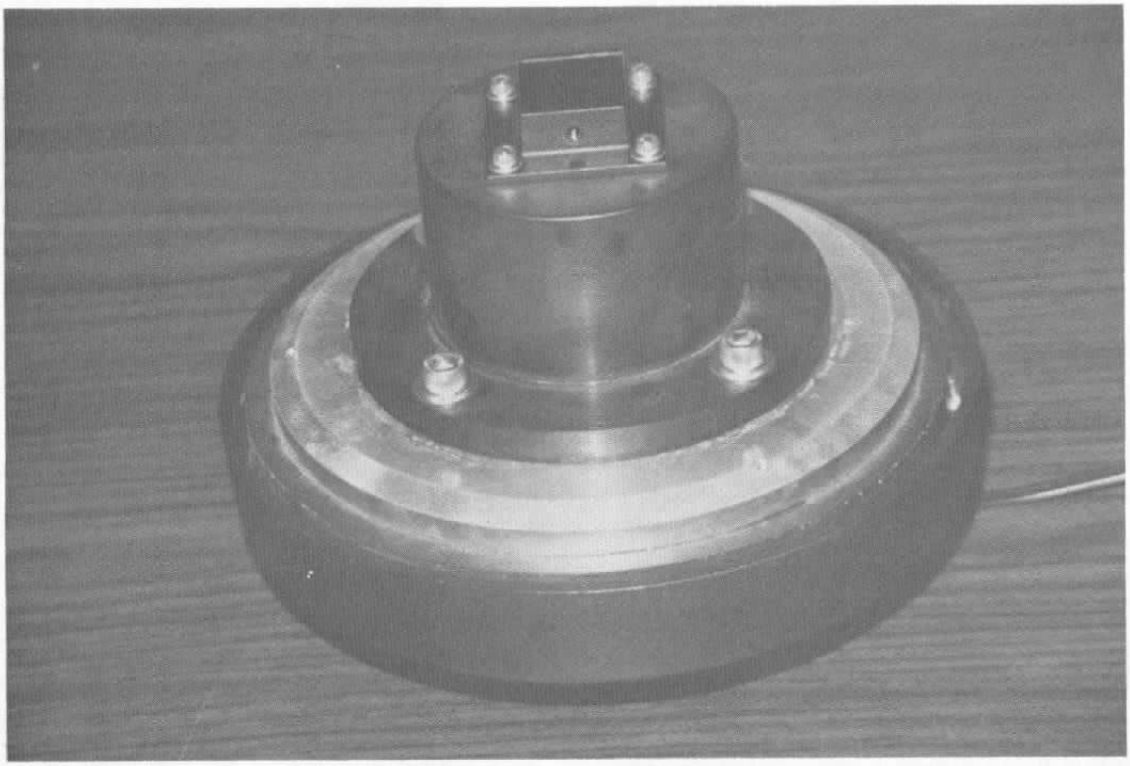


Figure 14. Acoustic cavity mounted to compression driver

used between the top of the piston assembly and the transducer mounting fixture to ensure a good seal. The fixturing mounted to the shaker is shown in Figure 15.

6. Development of Fixturing for Transducer Mounting

Prototype mounting fixtures were designed for three specific transducers:

1. a 0.5-inch-diameter flush-mounted transducer,
2. a transducer offset from the measurement point by 0.25-inch-outer-diameter tubing,
3. a rake transducer with five 0.93-inch-diameter tines separated by center-to-center distances of 0.287, 0.326, 0.384, and 0.495 inches.

The fixtures were designed with identical mounting configurations, so that each fixture could be bolted to either the compression driver/acoustic cavity fixture or the shaker/air piston fixture.

6.1 Interface between fixture and test transducer

To accommodate the test transducer, each fixture has a cylindrical bore slightly larger than the outer diameter of the test transducer with which it will be used. Three types of mechanisms were considered for sealing the interface between the test transducer and the mounting fixture:

1. an O-ring installed in a gland machined into the cylindrical bore,
2. an O-ring placed on the outer diameter of the transducer and captured between a plate (cap) and a countersunk bore in the mounting fixture, and
3. a rubber gasket installed between a plate (cap) and the mounting fixture (the gasket has an opening for the transducer of diameter slightly less than that of the transducer).

With the objective of simplifying future production of transducer fixturing, the third option was selected. This configuration was tested to ensure that test pressures could be maintained.

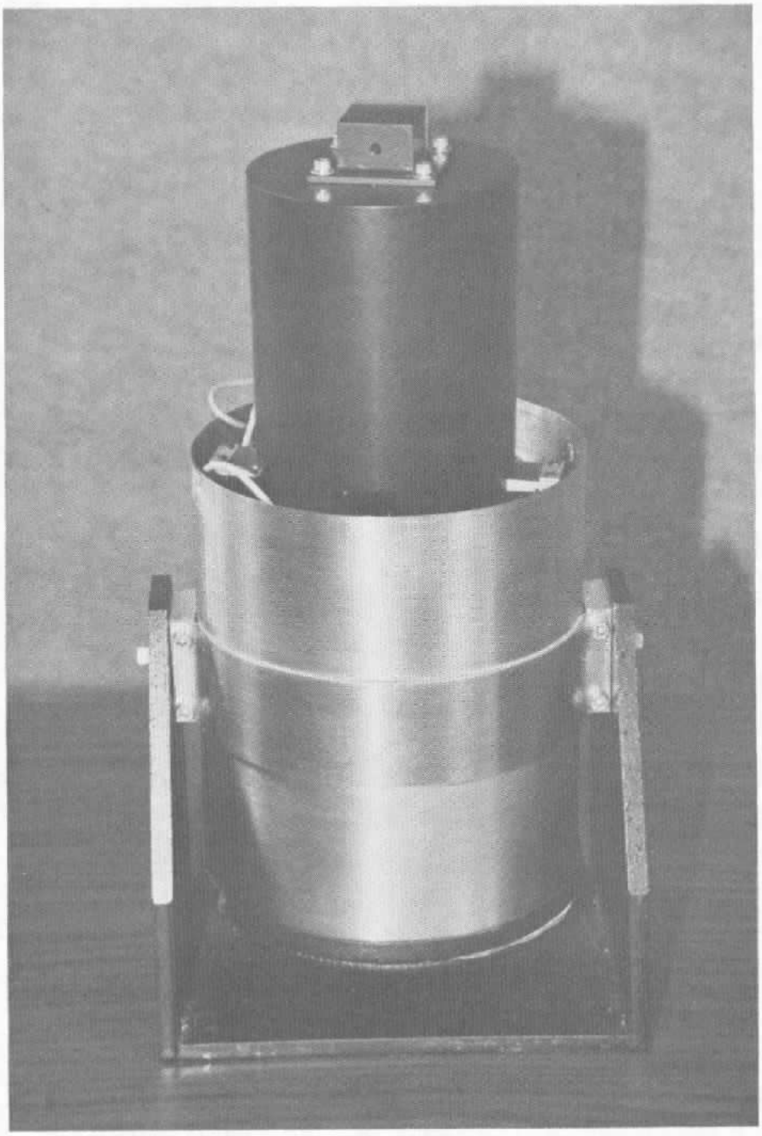


Figure 15. Fixturing for the shaker/piston assembly

6.2 Developmental testing

6.2.1 Relative orientation of standard and test transducers

Prototype transducer fixturing was manufactured and tested to verify performance and feasibility of the transducer mounting. In the original design, the reference transducer was positioned perpendicular to the test transducer in the fixture. This was done so that the sensing surfaces of the two transducers could be positioned as close together as possible. However, testing showed that two transducers in this orientation sensed slightly different pressures. This pressure difference increased with frequency and was unacceptable.

The design was modified. Instead, the two transducers were positioned opposite each other in a small cavity inside the mounting fixture. With this configuration, the transfer function of *reference sensor pressure/test sensor pressure* is equal to a value of 1.0 to at least 3500 Hz, well beyond the frequency range of interest.

Photographs of typical transducer mounting fixtures (without transducers) are shown in Figures 14 and 15, bolted to the shaker/piston fixture and the compression driver.

6.2.2 Axial positioning of transducers relative to fixtures

The positioning of each transducer relative to its fixture was another important design consideration. The standard (reference) transducer will always be the same transducer, the Endevco Model 8510B, so each fixture will have a 10-32 tapped hole. The depth of this hole is determined by the transducer geometry (0.438 inches). The shoulder of the transducer contacts the outer surface of the fixture as a positive stop, and the sensing surface of the transducer opens into the small cavity in the fixture, tangent to the cavity boundary.

The positioning of each test transducer depends on the geometry of the individual transducer. For calibration of a rake transducer, one tine is tested at a time, and the tines *not* under test are used to position the rake. In the prototype fixture, the tine under test is approximately 0.050" from the surface of the cavity in the transducer fixture.

Prototype fixtures for flush-mounted and tube-type transducers were designed so that the opening for these sensors is 0.003 inches (on the diameter) greater than the nominal diameter of the transducers. A small counterbore (0.020" on the diameter) provides a positive stop.

The depth of the counterbore used for the stop was determined by test. For sensors of diameter 0.25" or less, the sensing surface can be approximately tangent to the surface of the 0.5-inch-diameter cavity in the transducer fixture. This is not possible for sensors of diameter greater than 0.25". For the 0.5-inch-diameter transducer, a special test fixture was machined so that the transfer function of *test transducer pressure/reference transducer pressure* could be plotted for several positions of the test transducer relative to the fixture. Figure 16 shows the results of this test for three different positions. This test showed that the 0.5-inch-diameter transducer should be positioned so that it extends into the fixture cavity. For the prototype fixture, the test sensor extends about 0.15 inches into the cavity.

Drawings of the prototype transducer fixturing are shown in Appendix B. These drawings can be modified for other transducers so that additional fixturing can be produced as required.

7. Static Calibration

Instrumentation for static pressure measurement was incorporated into the system as a check for the dynamic calibration system. A manometer with a range of just over 1 psi was mounted on a test cavity designed so that the transducer mounting fixtures could be attached. This cavity is simply a capped aluminum cylinder of approximately 170 cubic inches. Pressure is generated in this cavity by pumping a hand-held squeeze-bulb (from a blood-pressure measurement sleeve obtained from a medical equipment supplier). The cavity is equipped with a pressure relief valve to insure that the transducers will not be damaged by excessive pressure. (The reference transducers are rated to 2 psi and can be safely subjected to about 4 psi.)

The pressure in the cavity can be set at some reference level, say 1 psi. The pressure is read on the manometer. Using a voltmeter to monitor the output of one of the pressure channels, the transducer factor of the combination of sensor and bridge amplifier is the ratio of the DC voltage reading and the static pressure reading.

8. Testing and Analysis of Final System Configuration

8.1 Admittance Model Prediction versus Test Result

The shape of the acoustic cavity that was developed to amplify the dynamic pressure at the transducers was selected solely as a result of the admittance model, before any hardware was manufactured. Once the cavity was machined, the results of test could be plotted versus the admittance model prediction. This comparison is shown in Figure 17. As stated previously, the generated dynamic pressure spectrum is not exactly as predicted by the model, but the amplification obtained in the bandwidth of 1600 to 2400 Hz is sufficient to attain the dynamic pressure design goal of 1 psi RMS.

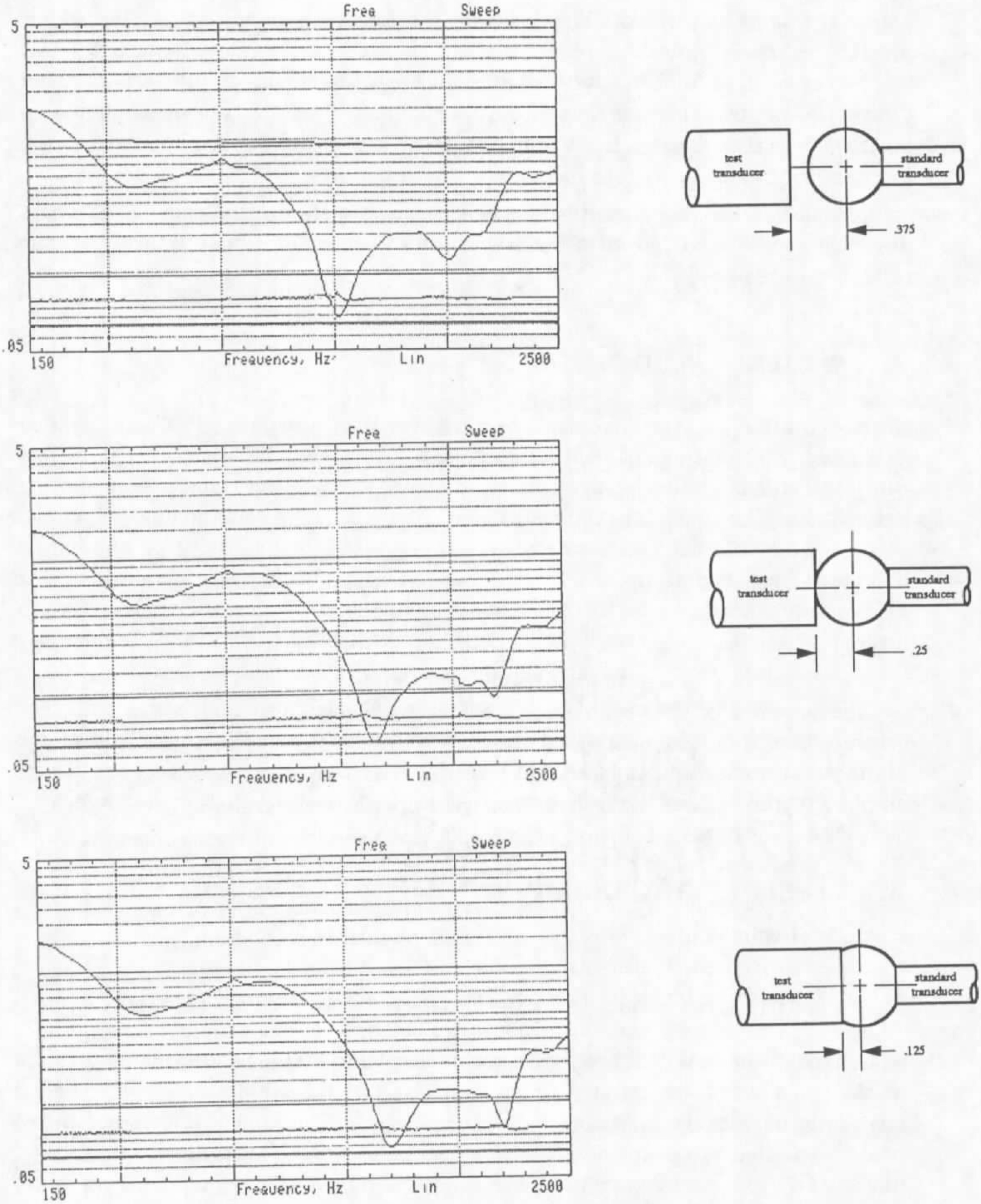


Figure 16. *Test transducer pressure/reference transducer pressure* for 0.5-inch-diameter transducer in various positions

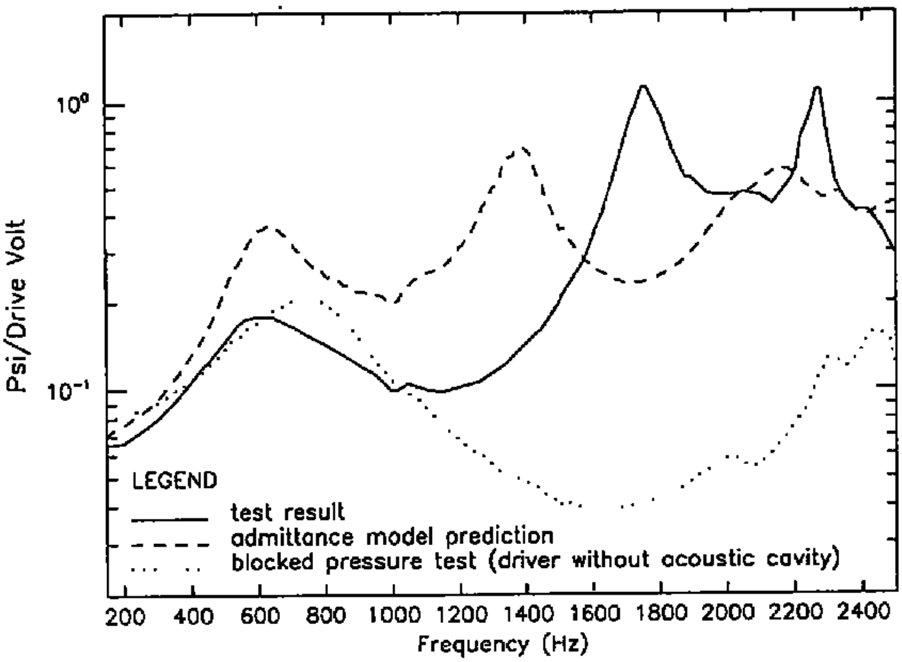


Figure 17. Comparison of admittance model prediction with test result

8.2 Calibration of Sensor/Tubing Configurations

8.2.1 Effects of tubing on pressure measurements

Many of the transducers that will be used with the pressure calibrator consist of sensor/tubing configurations, and analysis was performed with the finite element model of the selected cavity design (see Section 4.2) to predict the *pressure/drive voltage* transfer function at key locations in the combined cavity/tubing volume. This analysis verified that dynamic pressure measured in this configuration (at the end of a tubing volume) is dominated by the acoustic resonances of the tubing. Figure 18 shows a comparison of transfer functions generated at the reference and test sensors when a typical tubing segment (*diameter* = 1/4", *length* = 36") separates the test sensor from the cavity and reference sensor. This plot demonstrates dramatically that interface tubing changes the sensing frequency response function from what it would be if the test sensor were mounted directly to the cavity.[8] This figure also shows a plot of the ratio of the two transfer functions, representing the calibration curve for a test sensor with this particular tubing configuration.

[8]While it is intuitive that adding a tubular volume to an acoustic cavity will introduce a distinct low-frequency resonance and associated harmonics, in practice, it is easily overlooked.

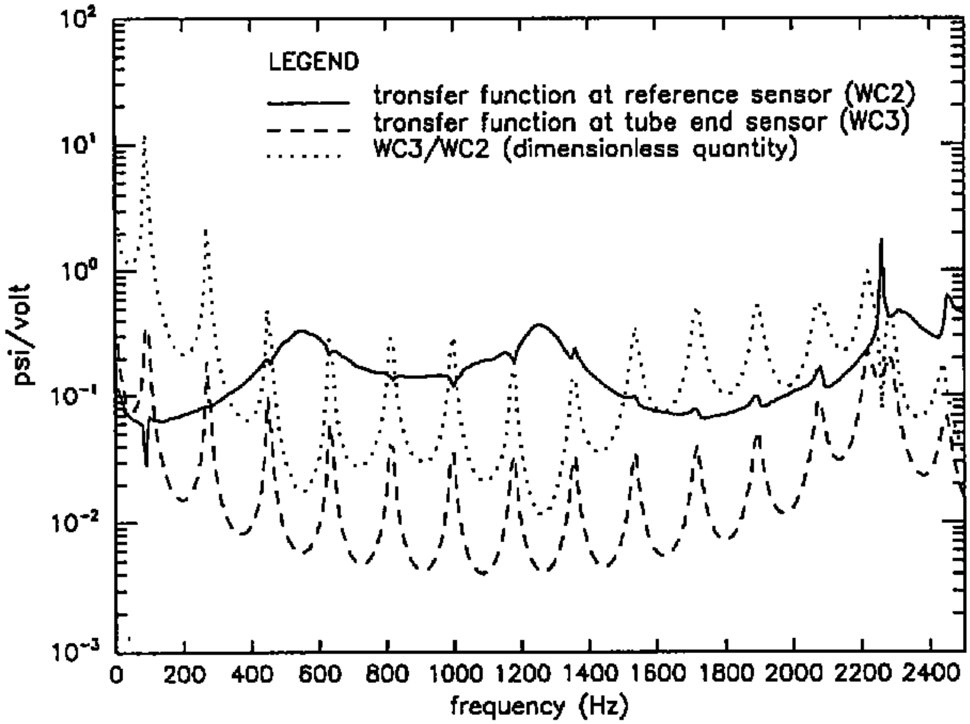


Figure 18. Comparison of transfer functions at reference and test sensors for a sensor/tubing configuration

8.2.2 Analytical comparison of standard transducer pressure and pressure at tubing entrance

Dynamic calibration data for a sensor/tubing configuration can be used in the same way as data for a non-tubing sensor only for low frequencies, i.e., below the frequency of the primary acoustic mode of the tube. Above this frequency, the tubing dynamics must be accounted for.

The design constraints established for the calibration system development were:

- the reference pressure in the acoustic cavity must be maintained when various tubing volumes are appended to the cavity, and
- the pressure at the inlet to the tubing must be equal to the pressure at the reference sensor.

Since it is impossible to measure directly the pressure at the entrance to a tube-type transducer without changing the pressure at that point, analysis was performed to compare *reference transducer pressure* to *pressure at the entrance to a section of tubing.* The finite element model of the acoustic cavity (see Section 4.2) was modified to include the added volume represented by a 3' x 1/4" segment of tubing. The admittance model was executed with this expanded model to predict the *pressure/drive*

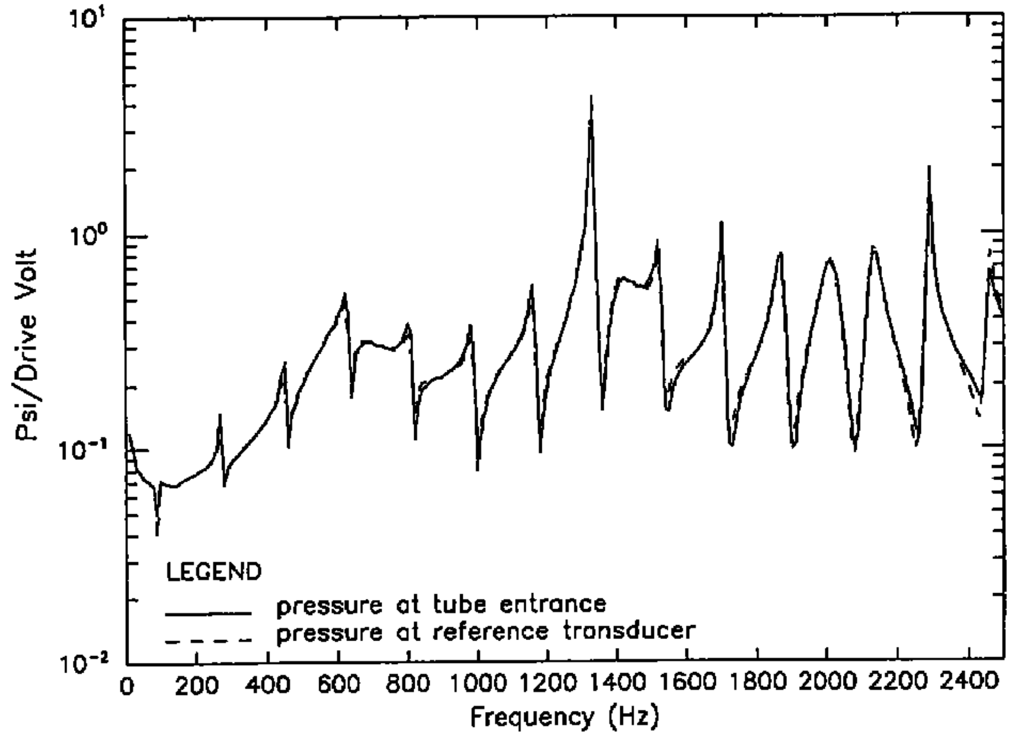


Figure 19. Comparison of transfer functions, *pressure/drive voltage*, at reference transducer and entrance to tubing

voltage transfer function at points representing the reference transducer location and the entrance to the tube. The results of this analysis are shown in Figure 19.

8.2.3 Tests with various tubing configurations

Tests were performed to measure reference pressures with various tubing configurations attached at the test transducer mounting location on the fixture. The pressure capability of the calibrator with tubing attached is diminished somewhat by the added volume of the tubing. Various tubing lengths were attached at the test transducer mounting location and the *pressure/drive voltage* transfer function was measured. Plots are shown in Figure 20 and Figure 21 for tubing lengths of 3' and 6'.

Similar tests were performed using the shaker/air piston configuration. As expected, at low frequencies, the dynamics of the tubing dominates the response. Figure 22 shows the pressure and drive voltage measured at the reference transducer with a 3' length of tubing attached at the test transducer mounting location. This test was performed with a control pressure of 1.0 psi. At 89 Hz, an anti-resonance due to the primary acoustic mode of the tube results in clipping of the drive voltage. (The drive limit had been set at 3 volts to control the input voltage to the shaker.) The result was a loss of the control pressure between about 65 and 105 Hz.

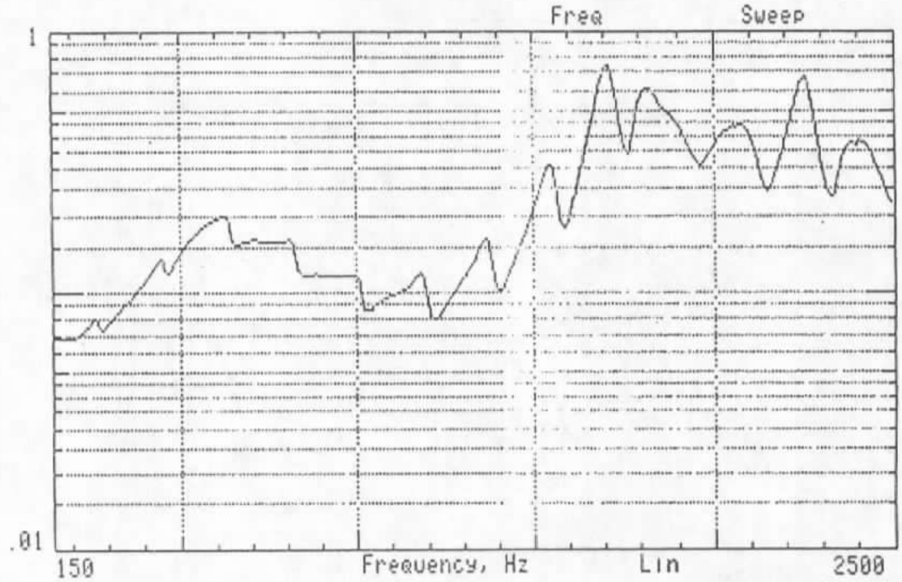


Figure 20. Typical *Pressure/drive voltage* transfer function at reference transducer with 3′ of attached tubing

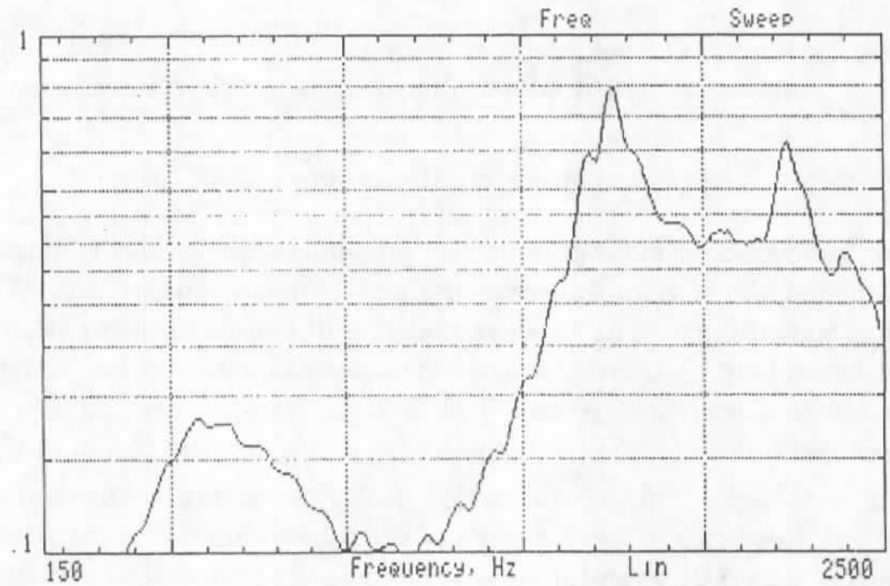


Figure 21. Typical *Pressure/drive voltage* transfer function at reference transducer with 6′ of attached tubing

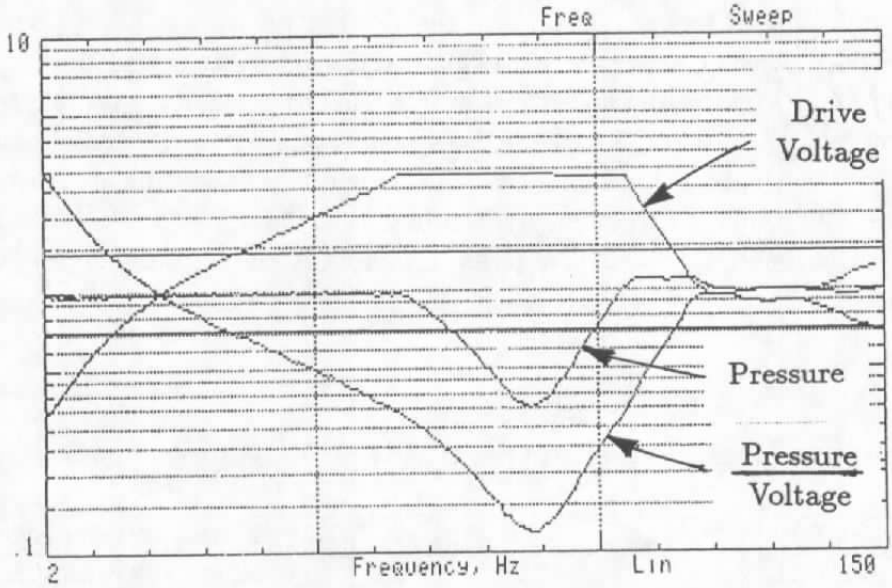


Figure 22. Typical *Pressure/drive voltage* transfer function at reference transducer with shaker excitation

8.2.4 Using the calibration system with sensor/tubing configurations

Use of the calibrator with sensor/tubing configurations is a valuable application of the system. A calibration curve, as in Figure 18, should be available whenever tubing is used with a transducer, to avoid misinterpretation of data.

9. Summary

This document is presented as a final technical report for the Phase II development of a dynamic pressure transducer calibration system (pressure response calibrator) under SBIR Contract No. F40600-89-C0004. A system has been developed based on concepts presented and investigated in Phase I of this contract. An innovative mathematical modeling tool known as admittance modeling was utilized to combine test data describing hardware with analysis data describing hypothetical acoustic cavity designs.

The Phase I development predicted that an acoustic compression driver could be used as the pressure source for a calibrator that would be capable of achieving 1.0 psi RMS over a frequency range of 2 to 500 Hz with sine excitation. However, results from extensive testing with a more powerful driver/amplifier combination and repetition of the Phase I configuration with a more sensitive transducer system showed that this prediction was in error. To achieve the desired pressure range (1.0 psi RMS) over the widest possible bandwidth, a dual-excitation system was developed. An electrodynamic shaker driving an air piston was used to provide the dynamic pressure over the bandwidth of 2 to 150 Hz. A 500-watt compression driver coupled with a cavity designed with acoustic resonances to provide pressure amplification was used as the pressure source for the frequency range of 150 to 2500 Hz. Table 1 lists pressure levels that have been obtained using this system. A photograph of the system is shown in Figure 23.

Frequency (Hz)	Pressure (psi RMS)	Waveform	Exciter
2–150	1.0	sine or random	piston
150–1600	0.25	sine	diaphragm
150–1600	0.4	random	diaphragm
1600–2400	1.0	sine or random	diaphragm
2400–2500	0.25	sine	diaphragm
2400–2500	0.4	random	diaphragm

Table 1. Summary of dynamic pressure capability of the calibration system

Figure 23. Pressure transducer calibration system

• APPENDIX A
GAMMA Formulation of Pressure Calibrator Admittance Model

```
! ADMITTANCE MODEL TO GENERATE CAVITY IMPEDANCES FOR
!     PRESSURE CALIBRATOR ADMITTANCE MODEL
! CAVZC11 = DRIVING POINT (ATTACHMENT "POINT") IMPEDANCE OF CAVITY DESIGN
! CAVZC12 = CROSS IMPEDANCE (SENSOR LOCATION TO ATTACHMENT "POINT")
PROJECT CAV
YES
GDOFLIST=DOFLIST
2X+,28X+,4X+      ! driving points
10x+,182x+,61x+  ! sensor locations

NDOFLIST=DOFLIST
2X+,28X+,4X+      ! driving points
10x+,182x+,61x+  ! sensor locations

DOFLIST=DOFLIST
2X+,28X+,4X+      ! driving points
10x+,182x+,61x+  ! sensor locations

MODE_LIST=LIST
1,2,3,4,5,6,7,8,9,10
11,12,13,14,15,16,17,18,19,20
21,22,23,24,25,26,27,28,29,30
31,32,33,34,35,36

SET NAME=CAVFUN
SET TITLE='CAVITY DESIGN'
SET SUBTITLE='PRESSURE CALIBRATOR'
SET ORDINATE_UNITS='psi/(in/sec)'
SET ABSCISSA_UNITS='frequency (Hz)'
SET LOWER=10.
SET DELTA=10.
SET POINTS=250
HMAX(2500.,2500.,2500.,2500.)
MODE_SET=NASTRAN_MODES(GDOFLIST,NDOFLIST,CAVOU2,CAVOU4,MODE_LIST)
SYNTH_CAV=SYNTHESIZE(DOFLIST,DOFLIST,MODE_SET,MODE_LIST,VELOCITY)
SHOW FUNCTION=SYNTH_CAV
STORE(SYNTH_CAV)
LOAD(SF1,2X+,10X+,1)
EDIT SF1
 CAVZC12
EXIT
PUT(SF1,SF,CAVZC12)
LOAD(SF2,2X+,2X+,1)
EDIT SF2
 CAVZC11
EXIT
PUT(SF2,SF,CAVZC11)
SINGLE(1,1,1)
MAG(1)
REAL(2)
IMAG(3)
TEXTURE(-,-.,..)
PLOT/HARD
TEXT_PAGE(1)
PLOT/HARD
SINGLE(2,2,2)
PLOT/HARD
TEXT_PAGE(2)
PLOT/HARD
```

APPENDIX A (cont.)
GAMMA Formulation of Pressure Calibrator Admittance Model

```
! ADMITTANCE MODEL FOR PRESSURE CALIBRATOR DESIGN
!   USING MEASURED TRANSFER FUNCTIONS (BLOCKED PRESSURE & KNOWN IMPEDANCE TESTS
!   AND ANALYTICAL TRANSFER FUNCTIONS FOR CAVITY DESIGNS
! WC2 - pressure/drive voltage AT OUTPUT END OF CAVITY
! WB - pressure/drive voltage FROM BLOCKED PRESSURE TEST
! WT - pressure/drive voltage FROM KNOWN IMPEDANCE TEST
! ZT11 - DRIVING POINT IMPEDANCE OF "INFINITE" TUBE
! ZD11 - IMPEDANCE OF EMILAR DRIVER
! ZC11 - DRIVING POINT IMPEDANCE (AT ATTACHMENT "POINT") OF ANALYTICAL CAVITY
! ZC12 - CROSS IMPEDANCE (SENSOR LOCATION TO ATTACHMENT "POINT") OF CAVITY
PROJECT CAVAMOD
Y
SET NAME=CAVFUN
SET TITLE='CAVITY DESIGN'
SET SUBTITLE='PRESSURE CALIBRATOR'
SET ORDINATE_UNITS='PSI/DRIVE VOLTAGE'
SET ABSCISSA_UNITS='FREQUENCY (HZ)'
SET LOWER=10.
SET DELTA=10.
SET POINTS=250
HMAX(2500.,2500.,2500.,2500.)

REAL (1)
IMAGINARY (2)
GET (SF1,PUNCH,WBREAL)
GET (SF2,PUNCH,WBIMAG)
SF2 = ADD(SF1,SF2)             ! WsubB=PsubDO/Vin
EDIT SF2
 WB



 10.
 10.
 Blocked P/V


 psi/volt
 freq (Hz)

 disp
 EXIT
 PUT (SF2,SF,WB)
 MAG(1)
 REAL(2)
 IMAG(3)
 TEXTURE(-,-.,..)
 SINGLE(2,2,2)
 PLOT/HARD

 REAL (1)
 IMAGINARY (2)
 GET (SF1,PUNCH,WTREAL)
 EDIT SF1
  WTREAL



  10.
```

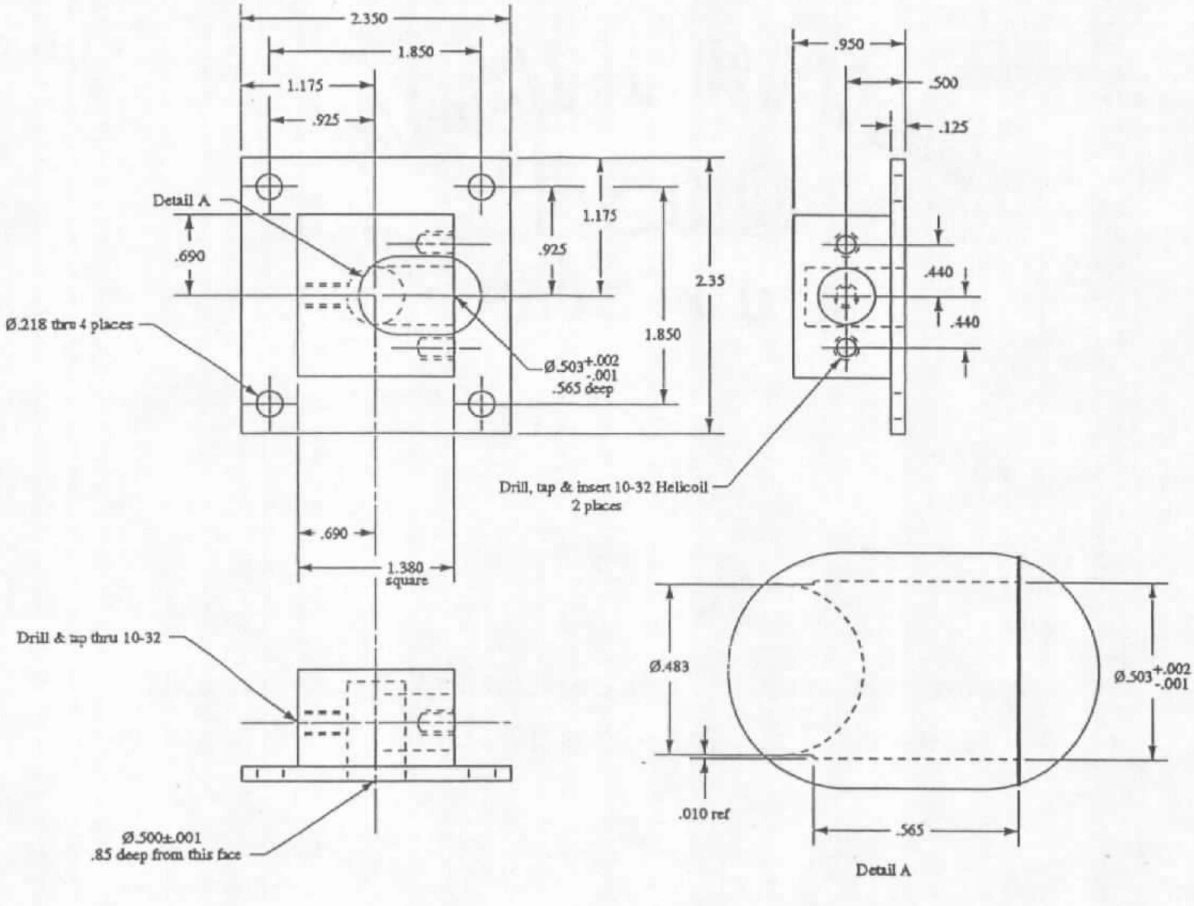
APPENDIX A (cont.)
GAMMA Formulation of Pressure Calibrator Admittance Model

```
 10.
 Infinite Tube P/V


 psi/volt
 freq (Hz)

 displacement
 EXIT
GET (SF2,PUNCH,WTIMAG)
SF2 = ADD(SF1,SF2)             ! WsubT=PsubT1/Vin
EDIT SF2
 WT
 EXIT
PUT (SF2,SF,WT)
MAG(1)
REAL(2)
IMAG(3)
PLOT/HARD

SF1 = CONSTANT(1.45E-3,0.)   ! ZsubT11=RHO*C=1.45E-3 LBF-SEC/IN**3
PUT (SF1,SF,ZT11)

GET (SF2,SF,WB)
GET (SF3,SF,WT)
SF1 = DIVIDE(SF2,SF3)
SF2 = CONSTANT(-1.,0.)
SF1 = ADD(SF1,SF2)
GET (SF2,SF,ZT11)
SF1 = MULTIPLY(SF1,SF2)       ! ZsubD11=((WsubB/WsubT)-1)ZsubT11
EDIT SF1
 ZD11




 Driver Impedance


 Impedance
 EXIT
MAG(1)
REAL(2)
IMAG(3)
SINGLE(1,1,1)
SET ORDINATE_UNITS='LBF-SEC/IN**3'
PLOT/HARD
PUT (SF1,SF,ZD11)

GET (SF2,SF,CAVZC11)
SF3 = CONSTANT(0.77,0.)
SF2 = MULTIPLY(SF2,SF3)
GET (SF3,SF,ZD11)
EDIT SF3
ZD11
```

APPENDIX A (cont.)
GAMMA Formulation of Pressure Calibrator Admittance Model

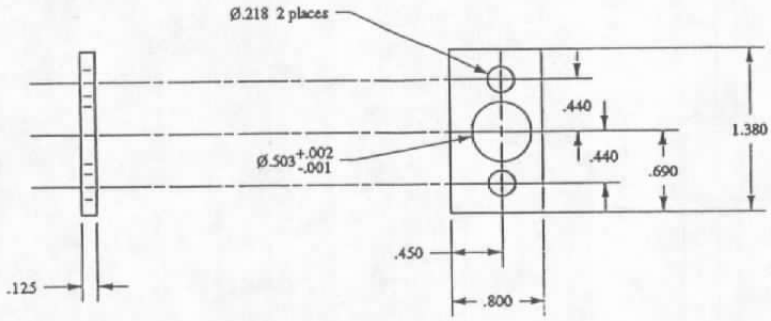
```
10.
10.
Driver Impedance


Impedance
Frequency (Hz)

DISPLACEMENT
EXIT
SF4 = ADD(SF2,SF3)                ! ZsubC11+ZsubD11
GET (SF2,SF,CAVZC12)
SF1 = CONSTANT(0.77,0.)
SF2 = MULTIPLY(SF1,SF2)
SF1 = DIVIDE(SF2,SF4)             ! ZsubC12/(ZsubC11+ZsubD11)
GET (SF2,SF,WB)
EDIT SF2
WB



10.
10.
Blocked P/V


Psi/Volt
Frequency (Hz)

DISPLACEMENT
EXIT
SF1 = MULTIPLY(SF1,SF2)           ! WsubC2=(ZsubC12/(ZsubC11+ZsubD11))
                                  !          *WsubB
PUT (SF1,SF,CAVWC2)               ! WsubC2=PsubC2/Vin
EDIT SF1
CAVWC2


1X+




Psi/Volt
EXIT
QUAD(1,1,1,1)
LOGY(1,3,4)
MAG(1)
PHASE(2)
REAL(3)
IMAG(4)
PLOT/HARD
LINY(1,3,4)
PLOT/HARD
SINGLE(1)
PLOT/HARD
EXIT/FULL
```

• APPENDIX B
Drawings of Prototype Transducer Fixturing



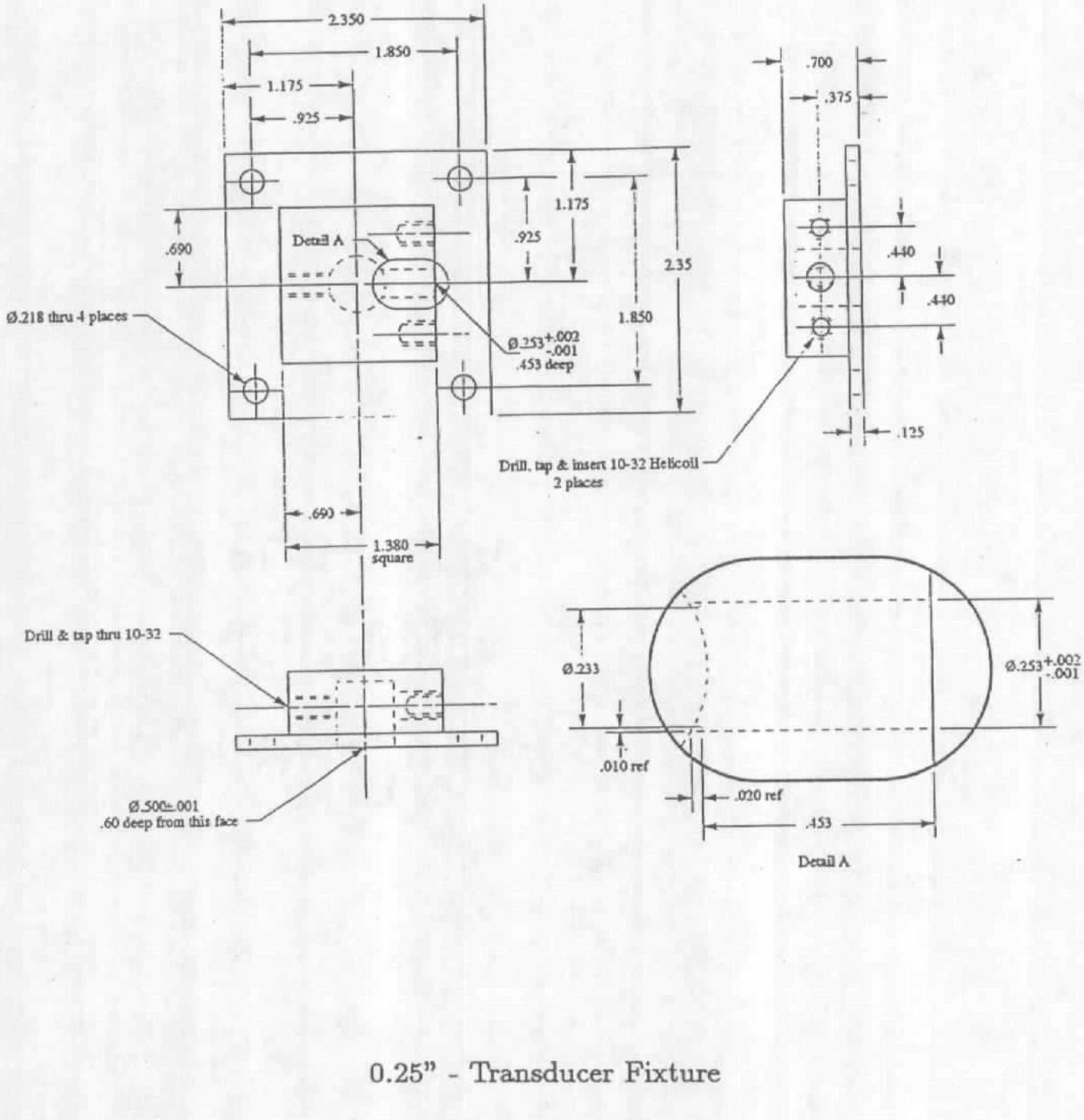
0.5" - Transducer Fixture

APPENDIX B (cont.)
Drawings of Prototype Transducer Fixturing



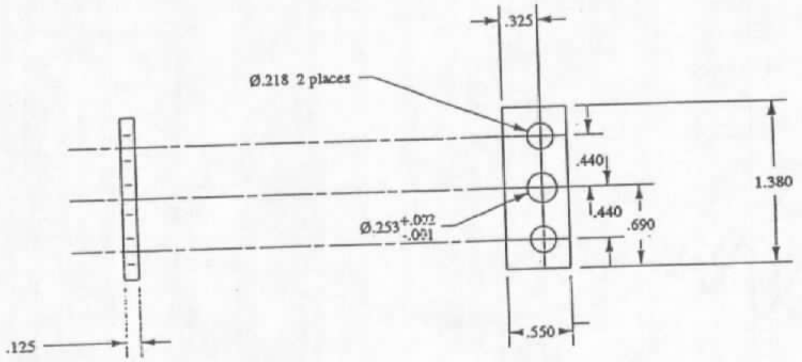
0.5" - Transducer Fixture Cap

APPENDIX B (cont.)
Drawings of Prototype Transducer Fixturing



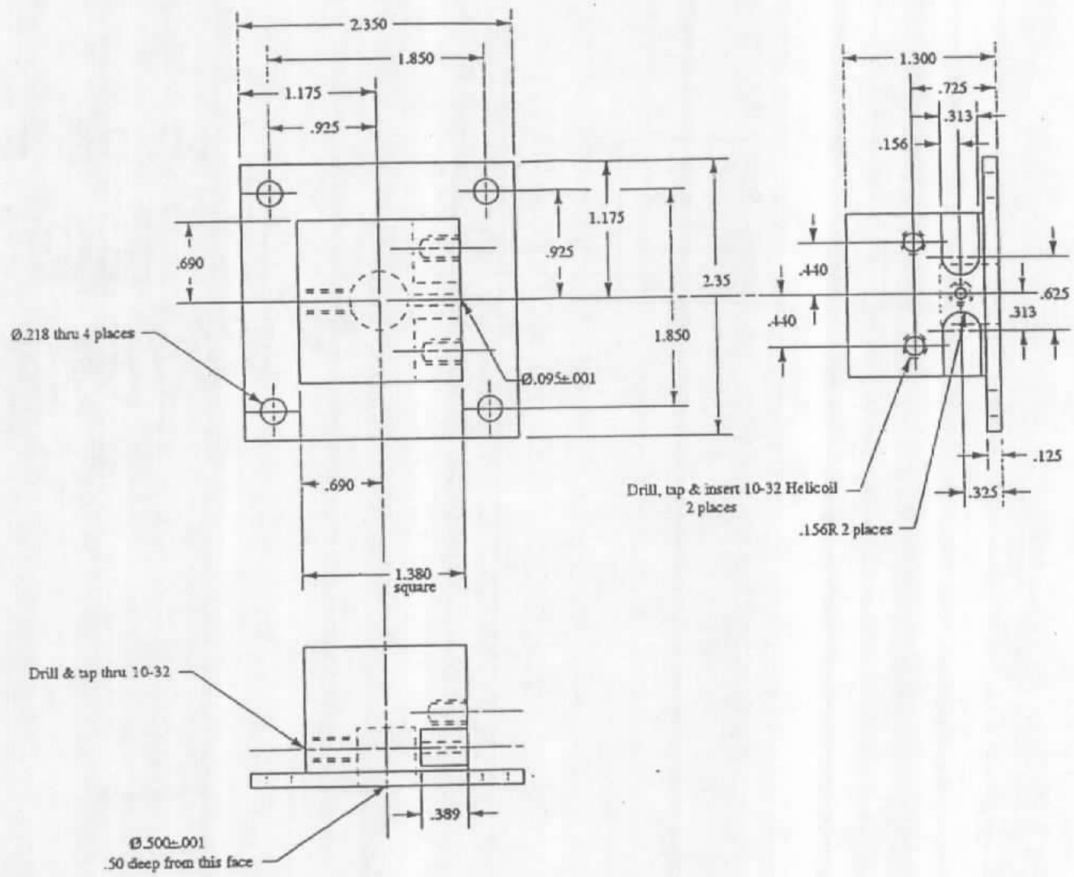
0.25" - Transducer Fixture

APPENDIX B (cont.)
Drawings of Prototype Transducer Fixturing



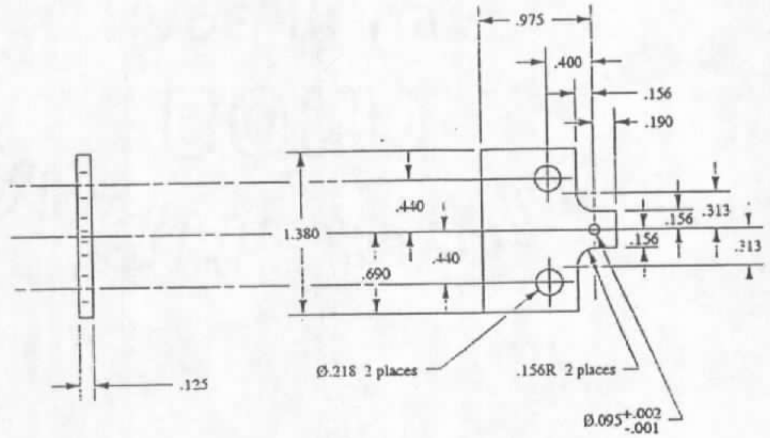
0.25" - Transducer Fixture Cap

APPENDIX B (cont.)
Drawings of Prototype Transducer Fixturing



0.093" - Transducer Fixture

APPENDIX B (cont.)
Drawings of Prototype Transducer Fixturing



0.093" - Transducer Fixture Cap